May 2020

Analysis of the Mechanical Properties of 3D Printed Recycled ABS

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ANALYSIS OF THE MECHANICAL PROPERTIES OF 3D PRINTED RECYCLED ABS

A Thesis

Presented to

the Graduate School of

Clemson University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Mechanical Engineering

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by

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May 2020

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ABSTRACT

With the increasing 3D printing user domain, the demand for the 3D printable materials has escalated. Since the development of this technology, several materials have been used to experiment with the printing process. The feasible materials for printing, range from various polymers to organic tissues. According to a study conducted by Forbes in 2018, plastics are the highest consumed 3D printing materials, accounting to about 88% of all the materials used at a global level. This is because, plastics are economically cheap and are readily available. The processability of plastics is relatively higher than other 3D printing materials.

The thermoplastic nature of ABS makes it suitable for 3D printing. Because of its composition, ABS has distinguished mechanical properties like good toughness, impact resistance, rigidity and strength. This makes ABS find its applications ranging from common household items to automotive parts and intricate medical devices. This increase in demand and usage of the material, resulted in the question of its recycling and disposal. Any improper disposal of ABS can be a very serious threat to the environment. Thus, this creates an increased scope for research on the recycling trends of ABS.

In this thesis, a system was designed to recycle ABS into a filament, so that it can be used as a 3D printing feedstock. In addition to that, a study on the recyclability of ABS to be reused as a feedstock for 3D printing has been conducted. To achieve this, commercially available virgin ABS polymer is reprocessed multiple times, until the material is degraded and can be no longer used as a feedstock for 3D printing. The behavior of mechanical

properties and the printability of recycled ABS polymer were investigated at each reprocessing cycle. This recyclate is then blended with virgin ABS at various percentages and the mechanical properties were investigated. The virgin ABS-recyclate blends were then processed multiple number of times. The printability and tensile properties were studied at every recycling cycle. Based on testing of recycled specimens, we observed aging effects that resulted in more brittle filaments. While some losses could be mitigated with the re-introduction of virgin materials in a blended material, aging effects continued to degrade the printed material.

DEDICATION

I would like to dedicate this thesis to my parents Mr. Ashok Kumar Ponnapalli and Mrs. Prashanti Ponnapalli, who always believed in me and my goals. Things would not have been possible without their constant love, support and encouragement. I also dedicate this work to my advisor, Dr. Cameron Turner, who was very patient at every step in this process and helped me develop a positive outlook towards my research outcomes. Lastly, this thesis is dedicated to all those people who are dealing with anxiety - panic disorders and are striving towards achieving their goals. You are not alone, and you can do it. Go strong!!

ACKNOWLEDGEMENTS

My deepest gratitude to my supportive advisor, Dr. Cameron Turner for his constant motivation and guidance throughout my graduate studies at Clemson University. I would like to thank my committee members, Dr. Hongseok Choi and Dr. Garrett Pataky for being a part of this research and for their inputs towards this study. I'm thankful to Dr. Pataky for providing access to tensile testing laboratory and his students for constantly helping me out during my experimentation. I would like to acknowledge the Machine Shop staff for helping me in building the necessary equipment and putting it together. I would also like to thank my friends and family who were with me and encouraged me in times of need.

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Chapter-1

Introduction

1.1.Problem statement

Determine the effect of recycling on the mechanical properties of ABS polymer for additive manufacturing.

1.2. Additive Manufacturing (AM)

Additive manufacturing is a process of joining materials to fabricate 3D components, usually layer upon layer, unlike subtractive manufacturing techniques [32]. In this process, initially, a 3D Computer Aided Design (CAD) model of the object is developed. This model contains the geometrical information of the object. It is then converted it into a standard AM file format such as STL (stereolithography) file format. In an STL file, the surfaces of the CAD component are approximated with triangles. In an STL file. This information is sent to a slicing algorithm, where the position, orientation or scaling of the object can be manipulated. The individual layer by layer machine code is generated here. Employing the generated code, the object is built layer by layer, by the AM machine [33].

Figure 1 Metal 3D printed manifolds for Land Rover BAR produced on Renishaw's additive manufacturing system

Source: https://resources.renishaw.com/gen/details/metal-3d-printed-manifold-for-land-rover-bar-produced-on-renishaw-additive-manufacturing-system--77114

Different AM processes build and reinforce the layers in different ways. Each AM process varies from the type of energy they use to melt down the material to the type of technique they use to deposit the layers on the print bed. Per ASTM standard F2792 [32], AM process is classified into seven categories: sheet lamination, fused deposition modelling, VAT polymerization, direct energy deposition, powder bed fusion, binder jetting and material jetting.

Fused Deposition Modelling (FDM) is an additive manufacturing process in which the part is fabricated by the extrusion of material through a nozzle in the form of a very thin filament (typically of diameter 0.4mm to 1.0mm). Usually, the material is heated to 1C above its melting temperature, for a quick solidification after the extrusion. This filament is deposited on to the bed, layer upon layer, following the path determined by the slicing software. Usually, the slicing software determines an optimized path by taking all the printing parameters like infill pattern, density, rafts, connections and bridging into consideration. The common materials that are used in FDM are thermoplastics like Acrylonitrile-Butadiene-Styrene (ABS), Polylactic acid (PLA), Polyamide (PA), High Impact Polystyrene (HIPS), Thermo-Plastic Elastomers (TPE), etc., metals like stainless steel, bronze, aluminum, titanium, etc., wax, graphene embedded plastics, concrete etc.

1.3.Growth of AM in the recent past:

Since its development, in the past 30 years, additive manufacturing (AM) has emerged from just creating prototypes to fabricating high quality end products. With its prominent role in the modern-day industries, additive manufacturing is often termed as the major reason for 'the third industrial revolution' [33]. The impact and applicability of additive manufacturing in various sectors has been increasing day by day. According to Wohler's report of 2016, the global demand for additive manufacturing machines has a very significant growth rate beginning from the year 2014 - amounting to be around 34.9%, when compared to that of previous year. As per Wohler's report of 2018 [37], the AM industry in 2017 had further growth rate of 21%, accounting to $7.336 billion of sales. Ruth Jiang and their group have conducted a Delphi study on economic and societal implications of 3D printing for 2030, to predict the future of additive manufacturing [35]. Their study indicates that, by 2030, more than 50% of the industrial additive manufacturing capacity will be in-house production capacity [35]. Their study also depicts that by 2030, majority of the consumers in the industrial countries will have additive manufacturing facility at their home [35], indicating a remarkable increase in demand for consumer grade AM machines in the near future. From these analyses, it can be depicted that, in the coming days, AM is going to be one of the prominent manufacturing techniques, both at consumer and commercial level.

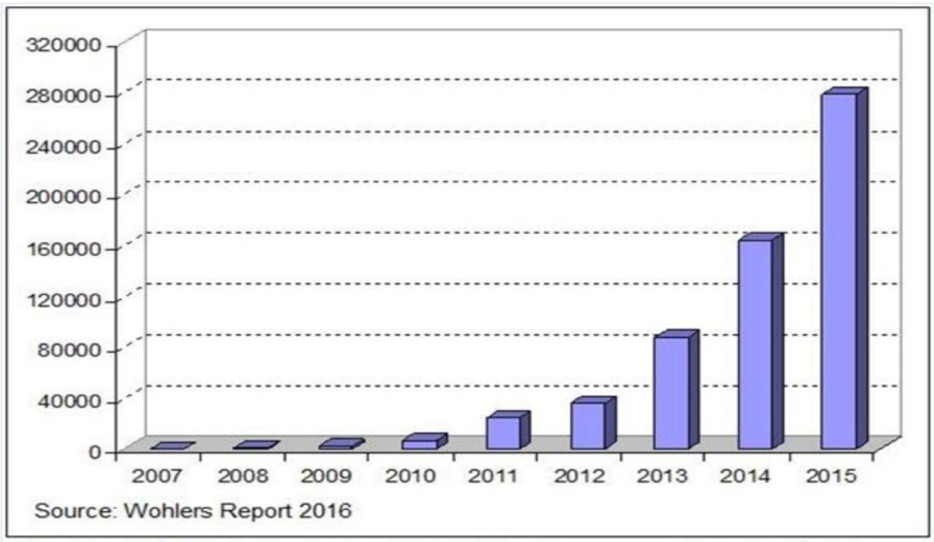


Figure 2 Wohler's report 2016 showing the trend of AM during the span of 2007 to 2015 (years Vs. no.of machines sold)

Source: https://wohlersassociates.com/press71.html

1.4.Why is AM growing?

The first patent for additive manufacturing technique was filed in the year 1986 [36]. This patent was expired in the year 2011, making the technology freely available for the public domain. Open source 3D printing technology emerged in early 2012. This resulted in the lowered costs of 3D printing machines as well as introduced the consumer grade 3D printing machines.

In addition to this, there are some other potential factors that give additive manufacturing (AM) an edge over the traditional manufacturing techniques [34].

1. Additive manufacturing produces minimal to no waste, when compared to traditional subtractive manufacturing methods while maintaining the same dimensional accuracy.
2. Additive manufacturing doesn't require additional fixtures and tools, like in traditional manufacturing. This saves the time and cost of additional tool manufacturing.
3. Intricate structures can be fabricated with ease, while maintaining geometrical accuracy. This technique doesn't require any manual skill or labor.
4. Mass customization and on-demand manufacturing can be achieved at very low cost with additive manufacturing when compared to conventional techniques.
5. In most of the cases, additive manufacturing eliminates the assembly of parts, by directly producing the end-product.
6. Any redesigns and modifications of the product can be made with minimal penalties. This reduces cost as well as time delays.

1.5. Industrial versus Consumer grade AM machines:

In 2005, the RepRap project, founded by Dr. Adrian Bowyer of the University of Bath, constructed a first at-home 3D printer. With the expiration of 3D printing patents in the early 21st century and availability of several user-friendly CAD tools, 3D printing has become an open source technique [36]. As 3D printing requires no machinery skill and allows people to create things as per their desire, it has captivated the interests of general public, encouraging the rise in demand for the consumer-level AM machines. Considering this interest of the public, several consumer grade 3D printer manufacturers have emerged. Though the price of first consumer grade 3D printer is around $5000/machine, it continued to fall to $150/machine, as of July 2019[36].

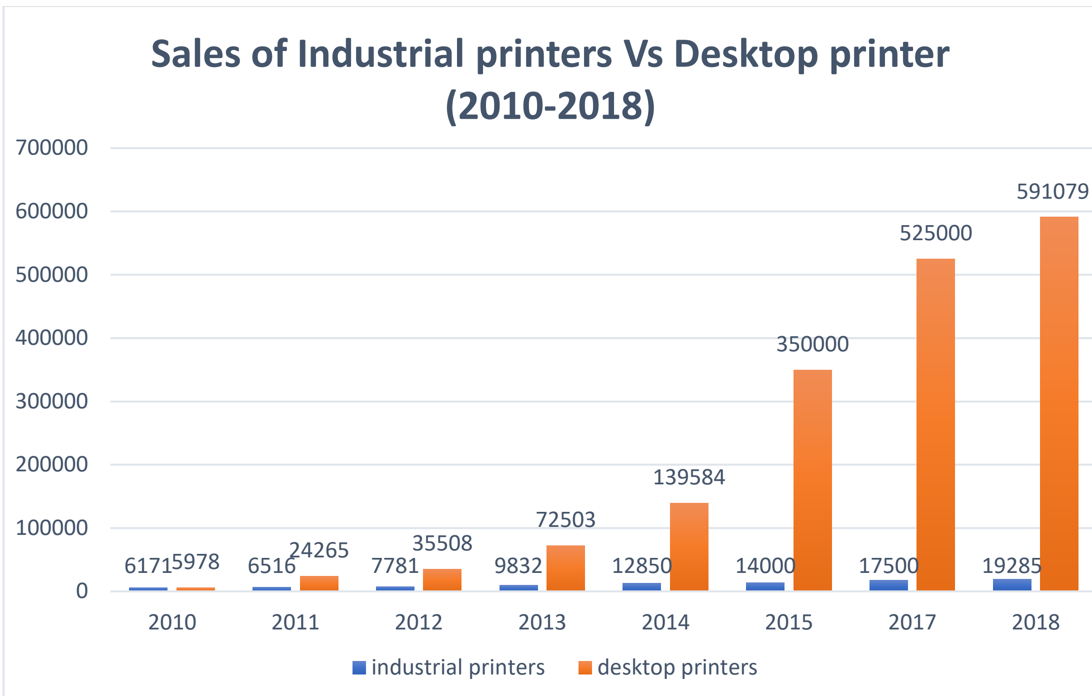


Figure 3 Sales of Industrial Vs Desktop 3D printer (2010-2018)

Source: 3D Printing: Overview, Impacts, and the Federal Role;

https://crsreports.congress.gov/product/pdf/R/R45852

In 2015, Wohler's report presented a comparison of sales of desktop 3D printers verses industrial 3D printers from 2010 to 2014. The report shows a very significant increase in the sales of desktop 3D printers in the year 2014 [38].

Some of the consumer grade 3D printing machines available in the market are-

1. MakerBot
2. Ultimaker
3. Formlabs
4. M3D micro 3D printer
5. Cube Pro

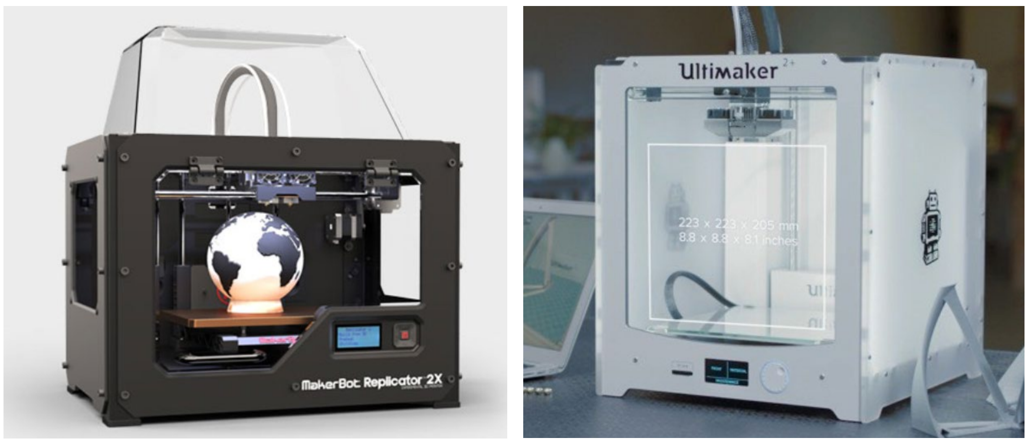


Figure 4 MakerBot replicator 2X and Ultimaker 2+ consumer grade 3D printers

Source: www.makerbot.com and www.ultimaker.com

1.6. Materials for AM:

With the adoption of 3D printing as a manufacturing technology, the demand for 3D printable materials have also increased. Since the development of this technology, several materials have been used to experiment with the printing process. The feasible materials for printing, range from various polymers to organic tissues. In 2018, Forbes conducted a study on consumption of different

3D printing materials during the years 2017-2018 [39]. The survey shows that plastics are the highest used materials for 3D printing.

Plastics have a wide variety of applications and are readily available, when compared to other materials. The applications of plastics may vary from prototypes for scientific and industrial research to common household objects.

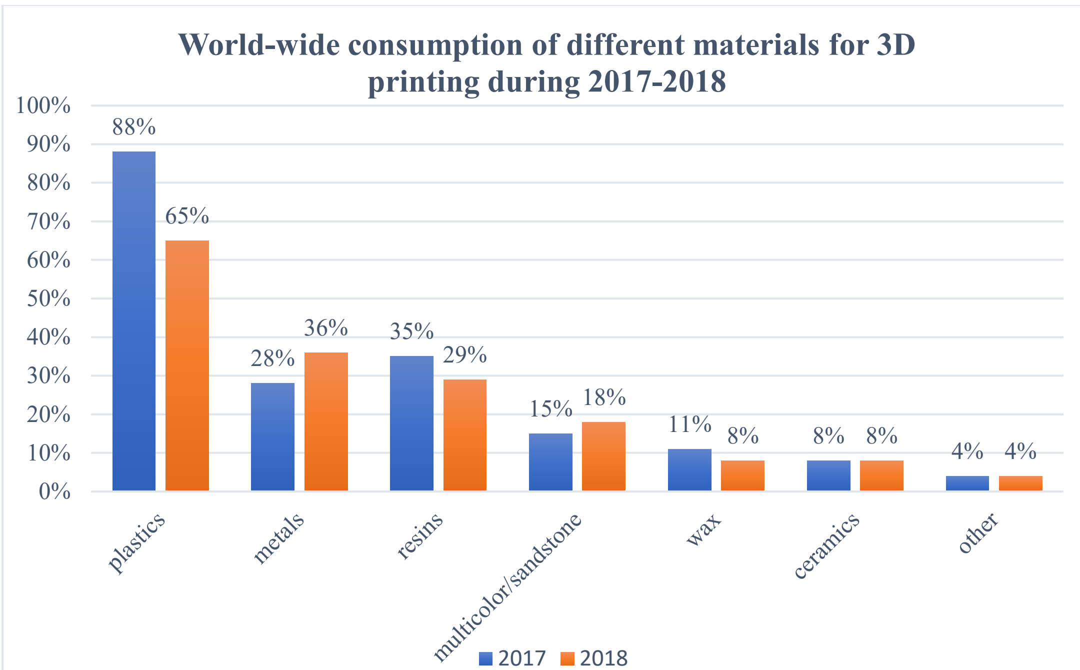


Figure 5 Worldwide consumption of different materials for 3D printing

Source: Forbes, Sculpteo's The State of 3D Printing 2018 [8]

1.7. ABS in 3D printing:

ABS is an opaque thermoplastic and an amorphous polymer with distinguishable mechanical properties like light weight, great toughness, impact resistance, hardness, shock absorbing capacity, scratch resistance and electrical insulation properties. It has a melting temperature of 200ºC, which makes it easy to work on and ideal for safer working environment. Because of these properties, ABS is a very good choice for household items, models, prototypes, tools and other end use applications. Commercially, ABS is available in the form of filament with diameters varying from 1.75mm to 3mm, in various colors. In addition to these, with slight variations in its composition and additives, ABS is available as ABS-M30, ABS-ESD7, ABS-M30i, ABS-si, PC-ABS.

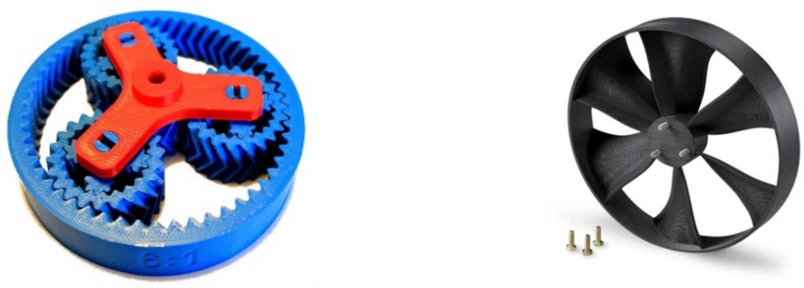


Figure 6 3D printed parts using ABS

source: www.thingiverse.com and www.proto3000.com

Properties of ABS:

S.No.	Property	ASTM Test method	Nominal value
1	Compressive strength	D695	60MPa
2	Hardness- Rockwell	D785	R105
3	Tensile modulus	D638	2.3GPa
4	Tensile strength @ yield	D638	40MPa
5	Flexural modulus	D790	75MPa
6	Flexural strength @ yield	D790	2.5GPa
7	Coefficient of linear expansion	D696	10.1 x 10-5 m/mC
8	Drying temperature	-	75C to 90C
9	Melt temperature	-	196C to 245C
10	Glass transition temperature	-	105C

Table 1Properties of ABS thermoplastic

Source: [9]

It's low melting temperature and low glass transition temperature have made ABS one of the best suited materials for the Fused Deposition Modelling. In this process, ABS filament of suitable diameter, is fed into the extrusion head of the printer where it is heated to its melting temperature. Once the material reaches its melting point, it is deposited on to the printing platform, layer by layer. The printing platform is also maintained at a temperature of 110C to keep the extruded plastic warm and reduce warping of the object due to the thermal gradients. The extrusion head can move along X-axis and Y-axis, while the printing platform can move along the Z-axis. The path of the extrusion head is determined by the slicing software. When deposition is completed, the printing platform is cooled to room temperature and the object can be removed from the platform.

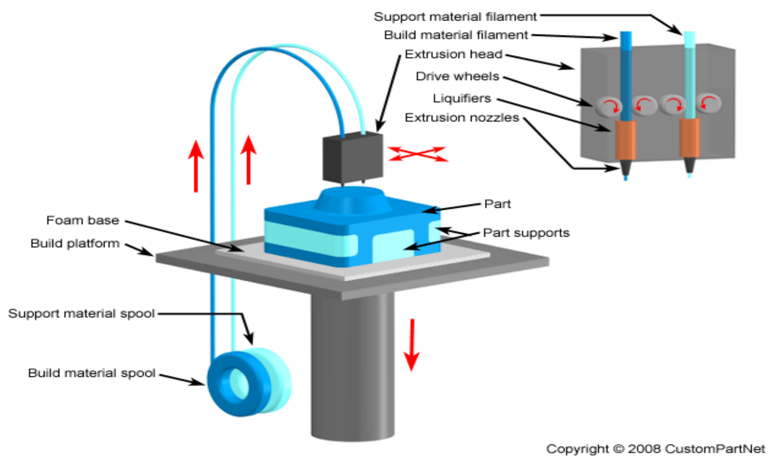


Figure 7 Schematic diagram of Fused Deposition Modelling

Source: mit.edu

1.8. Need for recycling of 3D printed ABS

According to Plastic Europe, the global plastic consumption was 335 million tons in the year 2015 and has increased by 3.68% when compared to the previous years. Because of its unique characteristics, ABS has its applications in electrical and electronic fields, automotive industry, housing appliances, medical and many other fields. However, disposal of this used ABS has become a serious threat to the environment. Therefore, there is a strong need to study the recycling trends of ABS and develop an appropriate recycling system to reprint it.

1.8.1. Waste reduction

Even though, 3D printing is an additive manufacturing technique, which is expected to produce zero wastage in the process, it still generates a significant amount of waste in the form of rafts, bridges and supports. The amount of material used in the form of rafts and supports depend on complexity of structure and finish of the printed object. More intricate structures require more material for the supports. In addition to this, plastic from the failed parts also contributes to the waste accumulation. So, studying about the process of recycling of such waste plastic and effectively using it to reprint the objects, helps in reducing or eliminating this wastage.

1.8.2. Economic issues

Currently, in the context of 3D printing, the average cost of a spool of ABS filament is 10$/lb. [40]. This price includes the cost of automated-manufacturing equipment, cost of skilled labor, transportation of materials, cost of marketing the product. This price can be reduced by decentralizing the manufacturing of filament and producing it at a smaller scale. The filament can be fabricated by the commercially available pellets or the recycled waste plastic. The filament from commercially available pellets can be manufactured at <22% of commercially manufactured filament cost. Also, the filament produced from the recycled waste can be manufacturing for $3/lb. [41], which is negligible when compared to commercially available filament in the market . The above statistics indicate a potential need for recycling of the waste plastic. This would also help in meeting the increasing demand for plastic in the coming future.

1.9. Can we effectively recycle and reuse ABS in FDM ?

The reasons stated in the section 1.8, provides us with a scope and need to develop a system, that can recycle used ABS and turn it in to 3D printing feedstock. In order to effectively reuse this ABS, one should have a knowledge on how the material behaves when subjected to recycling. So, this raises need for analysis of the mechanical properties for 3D printed recycled ABS.

The goal of this study is to find a best possible methodology to recycle ABS and analyze its properties, when recycled multiple number of times. This research concentrates on answering questions such as- what happens to the mechanical properties of ABS polymer when recycled to be reused as 3D printing feedstock? How does ABS polymer behave when recycled multiple number of times? If there are any losses in the material's properties, will the addition of virgin ABS material to the recycled recover any of it? If yes, what is the proportion of blended material at which the best properties could be obtained? If no, what happens to the mechanical properties when blended with virgin ABS?

Chapter 2

Literature Review

2.1 Recycling of Thermoplastic Polymers

Thermoplastic polymers are light, durable and inexpensive polymers. Because of their unique properties, the consumption of thermoplastics in additive manufacturing has increased remarkably. On the other hand, this increased consumption has led an increase in the discarded plastic that accumulated as debris in the landfill. Thus, recycling of thermoplastic polymers has been a topic of interest for many researchers for a very long time. Many efforts have been made to define a recycling process of these plastics. Some of them aimed for the reduction of solid waste while other worked for an economical advantage.

Thermoplastic polymers are made up of linear molecular chains, which makes them capable of softening when heated and hardening when cooled. This particular property of the thermoplastics makes them suitable for recycling. With the rapid expansion of research in this field, currently, thermoplastics can be recycled in three different ways – Chemical recycling, mechanical recycling, incineration [5].

2.1.1 Chemical Recycling [5]

It is a process in which the polymeric chains in the plastics are chemically broken down to monomers or oligomers through a reaction. These monomers are capable of further polymerization that can give rise to a whole new polymer or an original parent polymer. Some of the chemical reactions that are employed for this process includes – hydrogenation, glycolysis, gasification, methanolysis etc. Even though, this method of recycling breaks the polymers into smaller units making them suitable for reuse as feedstock, it involves higher costs and controlled operating environment. In addition to that, this process requires expertise and sophisticated equipment for successful output. Because of these reasons, chemical recycling is not widely used to recycle AM plastics today.

2.1.2 Incineration or Quaternary Recycling [5]

This process involves combustion of waste thermoplastic and reusing the heat energy generated from the process. The heat energy generated from this process can be various purposes like in production of electricity or heating up the buildings. Although this process is effective in recovering the energy content, it produces a lot of toxic biproducts involving potential health risks. So, this process proves to be ecologically harmful. In addition to that, this process is expensive as they involve kilns for burning the plastic and proper system to transfer the heat energy.

2.1.3 Mechanical Recycling [5]

This is a physical recycling technique. This process involves sizing the used plastic components into finer particles and re-melting it, to process into end-products. The basic steps in the mechanical recycling involves-

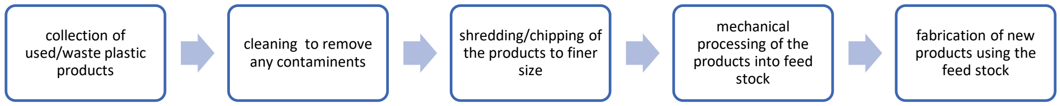


Figure 8 Basic Steps Involved in Mechanical Recycling of Thermoplastics

In mechanical recycling, used products from various target areas are collected initially. Later, these products are treated and cleaned for possible contaminants. Cleaning process can range from washing with water and air drying to treating with chemicals to separate impurities. In the next step, these products are shredding or chipped into finer size to make it suitable for mechanical processing. In this step the shredded material is usually converted into filaments, pellets or granulates to be used as feedstock for further manufacturing processes. This process also gives the scope of adding other materials and blending it with the recycled feedstock for desirable properties.

2.2 Traditional Recycling and Distributive Recycling

Depending on the place where the material is recycled, material recycling processes can be classified into two major types - Traditional recycling and Distributive recycling [6]. Distributive recycling is a process in which the waste material can be recycled at or near the place where it is produced. Cleaning and sorting of the waste material takes place at the same location where the waste material is reprocessed.

In this process, the output of the recycling process can be an end product or a feedstock for further manufacturing process.

Traditional recycling is a practice in which the waste material is collected from different locations and is transported to the recycling station. At the recycling station, the material is sorted and processed into some form of feed stock. Then, it is tested for the mechanical properties and is graded accordingly. This feed stock is then transported to different manufacturing locations to produce final products from it. This process involves a lot of logistics, energy and transportation costs. On the other hand, distributive recycling little or no transportation for the recycling process, which makes it an energy efficient and economically convenient process.

2.3 Mechanical Recycling of ABS Polymer

Acrylonitrile Butadiene Styrene (ABS) is an amorphous thermoplastic polymer. The composition of ABS polymer accounts for 15%-35% of acrylonitrile, 5-30% of butadiene and 40%-60% of styrene [23]. The properties of polymer vary with the combination of percentage of each component in it. Acrylonitrile is responsible for the thermal and chemical resistance of the material. Impact strength and ductility of the polymer is due to the presence of butadiene. Styrene imparts the glossy nature to the material. Because of this flexibility in the properties, ABS find a wide base of applications.

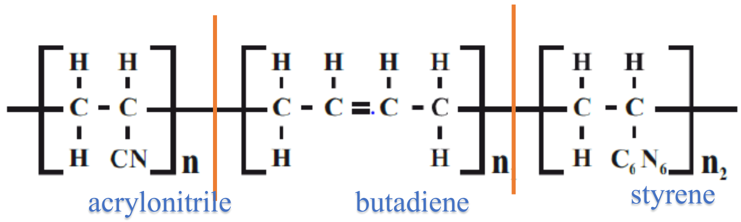


Figure 9 Chemical Composition of ABS

Because of thermoplastic nature and high consumer demand of this polymer, ABS is one of the target materials for recycling. Many industries are finding it as an opportunity to make their products environmentally friendly and at the same time to maximize their profits. Most of the applications of ABS polymer are fabricated through injection molding, extrusion or fused deposition modelling process. So, the end-product of mechanical recycling of ABS is usually in the form of pellets or filaments.

2.4 Mechanical Properties of Recycled ABS Polymer Fabricated Through Different Processes

Since the recycling of ABS polymer is a subject of demand, the study of mechanical properties is required for the proper utilization of the recycled plastic. Kim and Kang conducted a study on the mechanical properties of recycled high impact ABS, when fabricated through injection molding process [20]. According to their results, tensile strength, hardness and flexural modulus of the material remained same with the number of recycling cycles. However, impact strength of the material decreased with the increase in number of recycling cycles. A decreased of 5% in the polybutadiene content was observed after the 5th recycling cycle. As butadiene content in ABS polymer is responsible for the impact strength properties in ABS, it explains the decrease in the impact strength in the material, when recycled for multiple number of times. So, this concludes that the injection molding process has a degrading effect on the butadiene component of ABS.

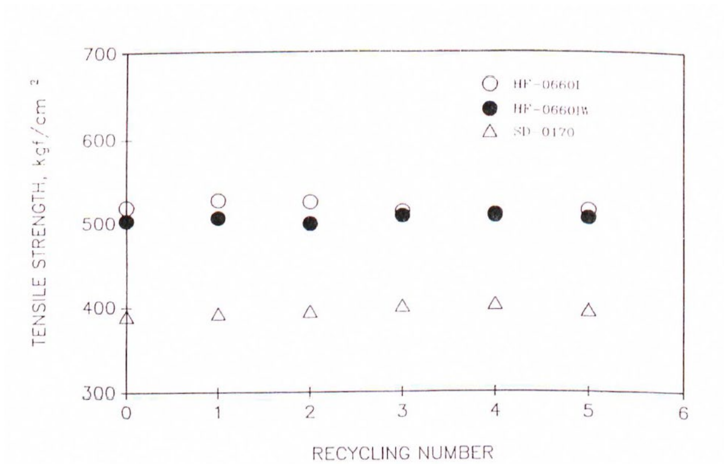


Figure 10 Effect of recycling number on tensile strength of SD-0170 – high impact ABS polymer

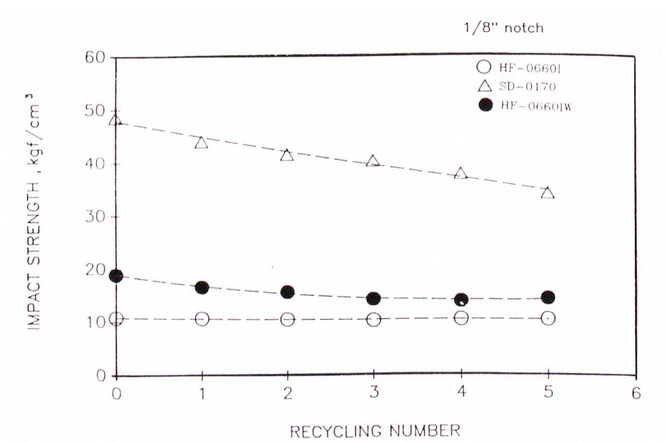


Figure 11 Effect of recycling number on the impact strength of high impact –ABS polymer

Source: http://www.tandfonline.com/doi/abs/10.1080/03602559508012182

Bai et al., studied the tensile and impact properties of recycled and injection molded ABS and the mechanical behavior with respect to the cycle number [21]. After one reprocessing cycle, they observed a drastic decrease of 44% in the impact strength of the material followed by a gradual decrease in the further cycles. Their study indicates that this phenomenon occurred due to the crosslinking of rubber phase (PB) and scissions in the polymer chains, which are more significant at the first processing cycle and showed a gradual trend in the later cycles. However, after the four reprocessing cycles, a slight increase in the tensile strength of the material is observed. They suggested that, this increase in the tensile strength might be due to degradation of the rubber phase and the loss of lubricant molecules due to the reprocessing. Their research gives a scope of research on further study of tensile properties of recycled ABS.

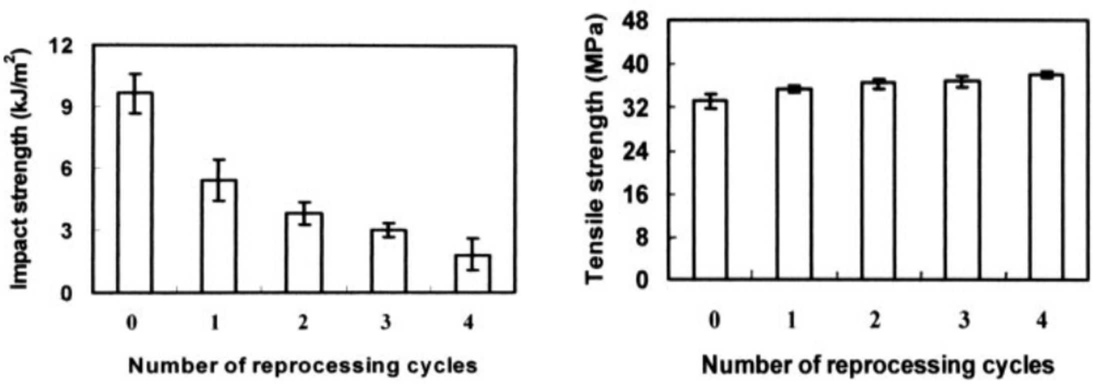


Figure 12 Effect of no.of reprocessing cycles on Impact strength and tensile strength

Source: https://doi.org/10.1177%2F147776061202800101

Antal Boldizar and their group conducted a study on degradation of ABS due to repeated processing and accelerated aging [19]. As a part of their study, they recycled ABS multiple number of times and employed sheet extrusion process to fabricate their specimens. They reprocessed ABS polymer for seven times and after the second cycle, they observed an increase in the elongation at break of the material, with increase in the cycle number.

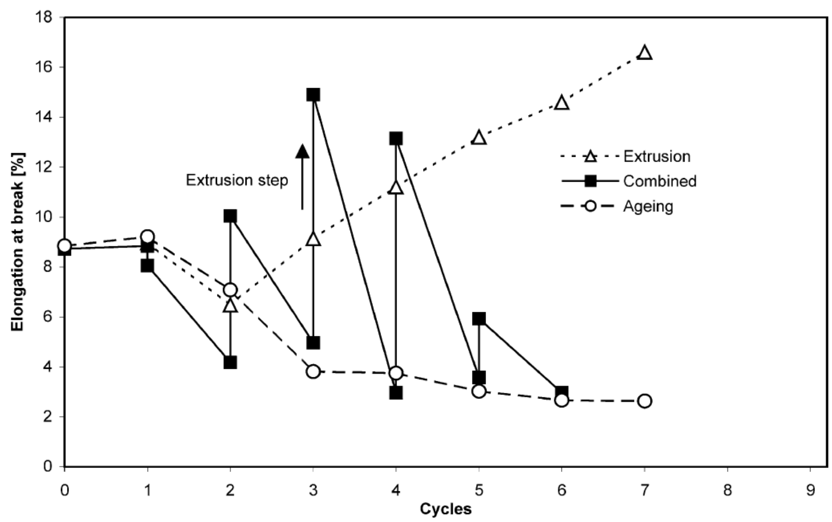


Figure 13 Effect of cycle number on elongation at break (%)

Source: https://doi.org/10.1016/S0141-3910(03)00107-1

R Scaffaro et al., studied the mechanical properties of virgin and post-consumer recycled blends of ABS [3]. In their study they observed after the first reprocessing cycle, tensile properties of the material decreased significantly. But the they did not find any further notable decrease in the tensile strength with the increase in the amount of recyclate or the reprocessing cycles. However, impact strength decreased with the increasing amount of recyclate and reprocessing. They suggested that this behavior of the tensile properties is due to presence of degradation kinetic at the initial stages i.e., when the molecular weight and the mechanical stresses are larger, the degradation is faster [5].

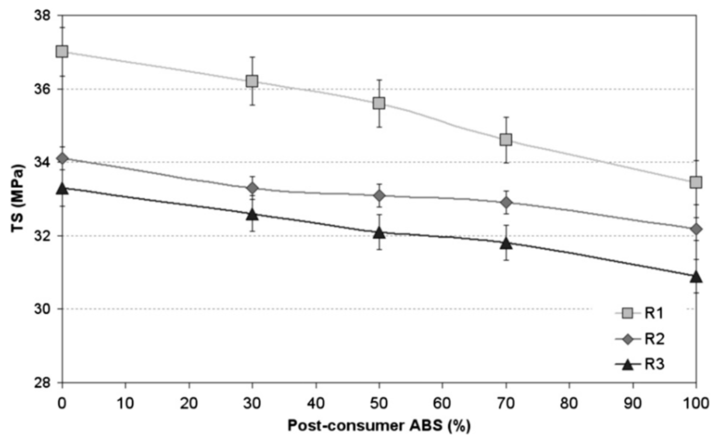


Figure 14 Tensile strength (TS) Vs Percentage of recycle ABS

Source: https://doi.org/10.1016/j.eurpolymj.2011.12.018

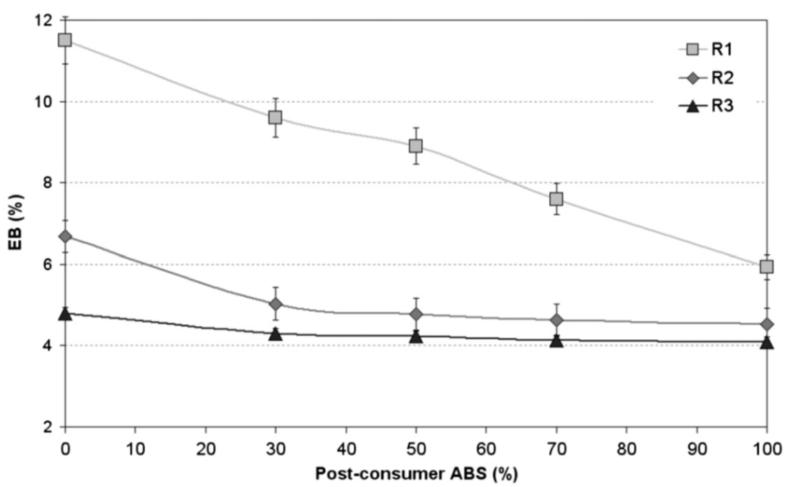


Figure 15 Elongation at break (EB) Vs Percentage of recycle ABS

Source: https://doi.org/10.1016/j.eurpolymj.2011.12.018

2.5 ABS Recycling in the context of 3D printing

ABS is one of the most commonly used material for 3D printing feedstocks. With the rapid increase in the usage of 3D printers in the recent past, the demand for ABS also increased in the same fashion. Although 3D printing is an additive manufacturing process that involves a little or no waste of the material, very often this process can generate waste in the form of failed prints, rafts or additional supports. As ABS is not a biodegradable polymer, any improper disposal increases the landfill pollution and would lead to serious environmental problems. Additionally, because of the increased usage and demand, the costs of ABS in the form of 3D printing feedstock has significantly gone up when compared to granulated ABS. Currently, the cost of 3D printing ABS filament is \$10/1lb [40] whereas the cost of granulated ABS is \$3/1lb [41]. Thus, recycling of this material to reuse as feedstock would be an efficient way to tackle this situation. But, in order find proper applications for this recycled material, the user must have a knowledge of its mechanical and physical properties.

Mohammed et al.,[12,15] studied the recyclability of ABS to be reused as feedstock in 3D printer. As a part of their research, they recycled the failed prints of ABS material and extruded a filament with it. This filament was used as feedstock and tensile test specimens were printed. They conducted the print quality tests of both the virgin and recycled ABS by comparing the 3D topology scans. No significant difference was observed in the quality of both the prints. However, they observed a 13% to 49% of decrease in the tensile strength when compared to virgin ABS.

Even though, there has been a decrease in the tensile properties of the material, their study suggests that the material has displayed good printability even after recycling. This gives a scope for on research on how the material would behave when subjected to further recycling and to what extent it can be recycled.

	Commercial Filament			Recycled Filament		
Sample	Ultimate Strength (MPa)	Average Stiffness (N/mm)	Strain at Failure (%)	Ultimate Strength (MPa)	Average Stiffness (N/mm)	Strain at Failure (%)
X Build	40.59±1.42	430.50	10.35±1.73	35.44±2.01	357.40	11.62±1.13
Y Build	42.34±0.88	419.78	6.62±0.28	29.06±1.21	302	6.36±0.18
Z Build	33.25±0.66	404.05	4.62±0.51	16.81±0.66	329.80	2.47±0.23

Table 2 comparison of mechanical properties of commercial and recycled ABS filament

Source: https://pdfs.semanticscholar.org/9cad/2f0c1362c2b039cd96a9ef687545137523c0.pdf

2.5.1 Chemical composition of ABS when subjected to melt processing

ABS polymer is composed of – acrylonitrile, butadiene and styrene. The acrylonitrile and styrene components are in continuous phase and are partially grafted to a dispersed phase of polybutadiene. This dispersed butadiene phase is responsible for the unique tensile and impact properties in the ABS material. According to H. Blom and their group [43], this butadiene phase of ABS is the one which gets effected when subjected to melt processing. Their group conducted a study on the detection of degradation in ABS by correlating the DSC, mechanical testing and oxidation onset temperature analyses. They concluded that the degradation of butadiene phase of ABS is responsible for the deterioration of the mechanical properties in the samples. They also suggested that, the occurrence of this phenomenon is due to the presence of the double bonds in this phase. These double bonds are susceptible to oxidation when subjected to melt processing (such as extrusion and injection molding). This oxidation in turn is responsible for the material degradation. Also, they observed that, this deterioration occurred in rapid phase at elevated temperatures in the presence of oxygen.

2.6 Extrusion of filament – 3D printing Feedstock [42]

Polymer extrusion is a traditional manufacturing technique. In order to transform used ABS into 3D printing feedstock, the material must be extruded into a filament with a specific consistent diameter, so that it can fed conveniently into the printer. The design and operating parameters of an extruder plays a crucial role in the quality of the filament. An extruder consists of three important zones of material processing.

2.6.1. Feed zone:

Material from the hopper is collected in this zone and is transferred to further processing zones within the extruder. The polymer is preheated in this zone. The typical length of this zone constitutes up to 5 to 6 turns of the extruder screw. Drag induced solid conveying of the material takes place in this zone of the extruder. For better conveying of the material the barrel and the extruder screw must be designed for [42] -

a. Minimizing rubbing forces on the barrel;

b. Minimizing rubbing force on the screw;

c. Higher ratio of barrel inner surface area to screw surface area; and

d. Gradually increasing pressure profile along the screw.

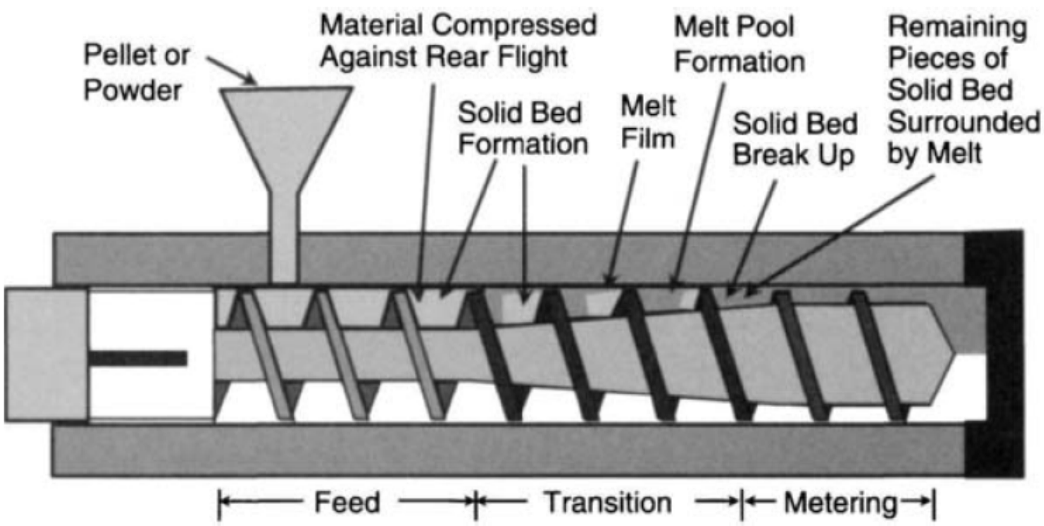


Figure 16 schematic of a single screw extruder

Source: https://kundoc.com/pdf-screw-design-.html

2.6.2. Transition zone:

This is the zone of the extruder in which the material will start plasticizing. Traces of both solid and melt forms of the material are found here. This phenomenon in this zone is explained by the Tadmor's model.

Tadmor's Plasticizing Model:

According to this model, once the melting process in the barrel begins, a melt film will be formed on the inner surface of the barrel. This film will keep increasing in thickness as more material gets melted and accumulated. The melt film conducts heat into the solid bed, creating a melt-solid bed interface. When the thickness of the melt front becomes greater than the radial flight clearance, the melt will flow into the screw channel, accumulating into a melt pool between the solid bed and active flight flank. This pushes solid bed upwards and makes it to come into contact with hot barrel surface, thus creating another melt film. The active flight flank conveys the melt pool further towards the metering zone of the extruder.

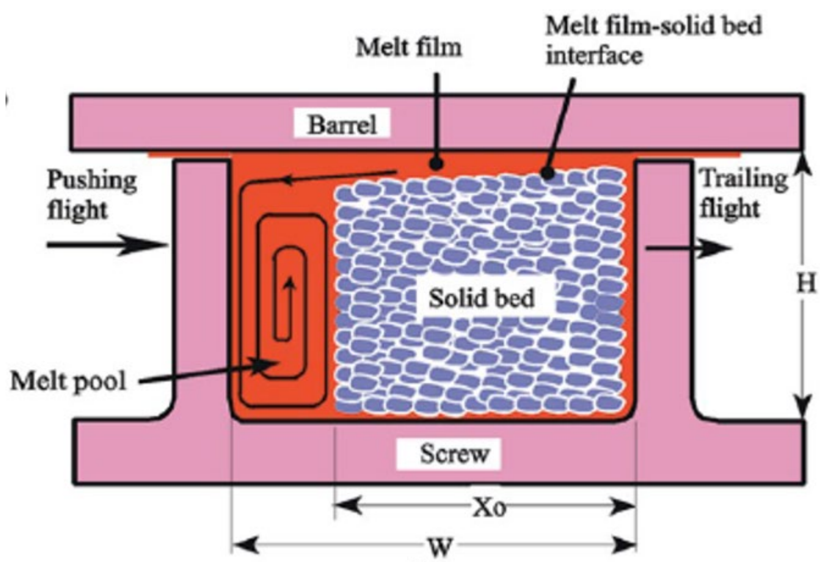


Figure 17 schematic of a Tadmor's Model inside extruder's barrel

Source:https://www.hanserpublications.com/SampleChapters/9781569904596_9781569904596_Extrusion%20of%20Polymers%202E_Chung.pdf

According this model, the preferred conditions for a high melting capacity in the process at give screw speed are-

a. Barrel temperature should be greater than the melting point of the polymer;
b. Large Solid bed - barrel contact area;
c. Smaller channel width;
d. Preheated feed; and
e. Flight clearance should be tight.

2.6.3. Metering zone or Melt Conveying Zone:

This zone starts after the transition zone, where the melting of the material is complete. Here the melted plastic sticks on to the screw and rotates along with it. A part of it is held back by the barrel. That part of material is dragged by the barrel. Because of the geometry of the screw's channel, that material gets detached from the screw and gets pushed forward towards the die opening. This phenomenon caused by the drag is called "drag flow". In addition to this, a "backward flow" is also present inside the barrel caused due to the pressure drop. Therefore, the "net flow" is responsible for the movement of the melted material in the metering zone.

Theoretically,

$$(\textit{Material flow rate})_{net} = \textit{drag flow rate} - \textit{backward flow rate} \qquad \textit{Equation 1}$$

2.7 3D Printing Parameters – Influence on the Mechanical Properties

The print quality of a specimen depends on the printing parameters that are used. Optimal value of the printing parameters such as nozzle temperature, bed temperature and printing speed are different for different materials. K.G. Jaya Christiyan and their group worked on the influence of the processing parameters on the mechanical properties of 3D printed ABS ASTM-D638 and ASTM-D790 specimens [2]. As a part of their study, for testing the tensile and flexural properties of ABS, they printed different specimens by varying the printing speed from 30mm/sec to 50mm/sec and sample layer thickness from 0.2mm to 0.3mm. They observed a highest ultimate strength of 28.5 MPa, when the sample was printed at 0.2 mm at a speed of 30mm/sec. They concluded that better tensile properties were evident in the samples with lower thickness and lower printing speed, as there was a better bonding between the layers of these specimen when compared to ones printed at higher speed and layer thickness. So, these printing parameters were adopted to print the specimens in the current study.

In general, the properties of a material change with every recycling cycle it undergoes. Hence, the knowledge of printing parameters with which the recycled material must be printed is necessary. Aubrey L. Woern and their group worked on the recycled materials optimization and material properties [4]. As a part of their study, they analyzed the optimum processing parameters for 3D printing with different recycled polymers. According to their results for 3D printing with recycled ABS, the optimum extruder head temperature is 240 C and the print bed temperature is 90 C. On the other hand, virgin ABS is printed at a temperature of 215 C in extruder head and 100 C in the print bed. This difference in the processing parameters for the virgin and recycled ABS, gives us a scope to further study on the variation of 3D printer setting with respect to recycling cycle number.

2.8 Tensile Test Methods for 3D Printed ABS:

ASTM international[1] has defined D638 standard to study the tensile properties of the polymers. The following are the five types of tensile test specimens that are set by ASTM and are operated globally.

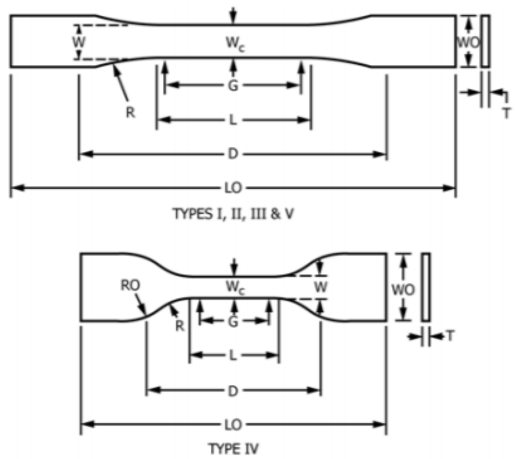
a. ASTM D638 type – I: It can be used for rigid, semi rigid and reinforced, unreinforced composite materials.

b. ASTM D638 type – II: It can be used when the material does not break in the narrow section with preferred type-I

c. ASTM D638 type – III: It can be used for all the rigid and non-rigid plastics where the material thickness is greater than 7 mm but less than 14 mm.

d. ASTM D638 type – IV: It can be used for non-rigid plastics and when the available material is limited, and thickness of the material is less than 4 mm.

e. ASTM D638 type – V: It can be used for rigid & semi rigid plastics and when there is only limited material available for testing. The typical thickness of material for this type is less than 4 mm.



Specimen Dimensions for Thickness, T, mm (in.)[A]

Dimensions (see drawings)	7 (0.28) or under		Over 7 to 14 (0.28 to 0.55), incl	4 (0.16) or under		Tolerances
	Type I	Type II	Type III	Type IV[B]	Type V[C,D]	
W—Width of narrow section[E,F]	13 (0.50)	6 (0.25)	19 (0.75)	6 (0.25)	3.18 (0.125)	±0.5 (±0.02)[B,C]
L—Length of narrow section	57 (2.25)	57 (2.25)	57 (2.25)	33 (1.30)	9.53 (0.375)	±0.5 (±0.02)[C]
WO—Width overall, min[G]	19 (0.75)	19 (0.75)	29 (1.13)	19 (0.75)	...	+ 6.4 (+ 0.25)
WO—Width overall, min[G]	...	...	...	...	9.53 (0.375)	+ 3.18 (+ 0.125)
LO—Length overall, min[H]	165 (6.5)	183 (7.2)	246 (9.7)	115 (4.5)	63.5 (2.5)	no max (no max)
G—Gage length[I]	50 (2.00)	50 (2.00)	50 (2.00)	...	7.62 (0.300)	±0.25 (±0.010)[C]
G—Gage length[I]	...	...	...	25 (1.00)	...	±0.13 (±0.005)
D—Distance between grips	115 (4.5)	135 (5.3)	115 (4.5)	65 (2.5)[J]	25.4 (1.0)	±5 (±0.2)
R—Radius of fillet	76 (3.00)	76 (3.00)	76 (3.00)	14 (0.56)	12.7 (0.5)	±1 (±0.04)[C]
RO—Outer radius (Type IV)	...	...	...	25 (1.00)	...	±1 (±0.04)

Figure 18 Different ASTM Tensile Test Specimens

Source: Standard Test Method for Tensile Properties of Plastics ATM D638-14

3. Design of Filament Extruder

3.1. Filastruder

To recycle ABS polymer and make it into feedstock for 3D printer, a commercial filament extruder - Filastruder was employed. It is a tabletop filament extruder with the overall dimensions of 18inch×6inch×4inch. This system extrudes a filament of 0.75 mm, at a rate of 15 inch per minute. It has a single heating zone and is operated at 180 C.

Figure 19 Picture of the commercial filament extruder- Filastruder

Source: www.filastruder.com

3.1.1. Failure of the Filastruder:

Approximately after 15 hours of usage of Filastruder, the extrusion rate had drastically decreased to 2in/min. A change in the color from white to dark grey was observed in the filament. In addition to that, the extruded filament was very brittle in nature. The extruder stopped working when attempted to use it further.

3.1.2. Analysis of Filastruder's failure:

3.1.2.1 Metallic scarps in the filament:

When the extruded filament was exposed to magnetic environment, it showed a typical metallic behavior indicating the presence of metal in it. Also, this explains the brittle behavior of the filament. Later, the pellets that were used to extrude this filament were tested and they did not show any magnetic behavior. This concludes that the source of the metallic components was from within the extruder's barrel.

Figure 20 Filament with metallic scarps and clog at the nozzle filter

3.1.2.2 Erosion of the inner surface of the barrel:

In order to check if there was any contact between the auger and barrel inner surface, the auger was painted with a washable die and system is operated without any pellets in it. From this experiment, it was evident that a portion of auger is rubbing against the wall of the barrel, giving rise to the metallic scrapings in the filament. All these metallic scrapings were stuck on the nozzle melt filter, obstructing the material flow through the nozzle. This explains the drastic decrease in the extrusion rate of the filament.

Figure 21 Eroded Auger surface

3.1.2.3 Auger misalignment with motor shaft:

The auger in the system was connected to the motor shaft through a coupler. The coupler's support to the auger was insufficient to overcome forces developed during the extrusion process. This gave rise to a misalignment between the auger and motor shaft. This misalignment led to the contact between the auger and barrel.

3.1.2.4 Insufficient heating in the system:

The system had only one heating zone, located at the die of the extruder. So, the material will be in its solid form until it reaches the extruders nozzle. This imposes additional load on the auger. In addition to that, the material was exposed to a sudden higher temperature at the die, resulting in a thermal shock in the polymer.

3.2 Design of DICE Filament Extruder:

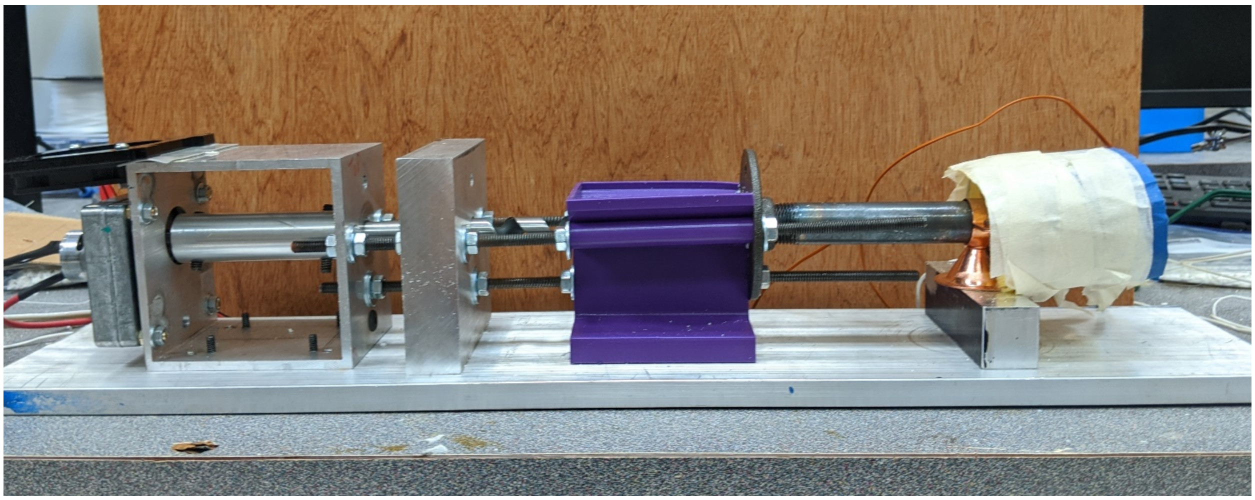


Figure 22 DICE Filament Extruder

An improvised filament extrusion system – DICE Filament Extruder was designed to eliminate the issues associated with the Filastruder. The design modifications can be categorized into -

3.2.1 Redesign of the feeding section:

For better material transfer, the solid centered 5/8-inch auger was replaced with a Jennings spiral bit 5/8-inch auger. Because of the absence of a solid center, this auger bit transfers more material when compared to the previous one.

Figure 23 5/8-inch spiral bit auger

Source:http://www.pabtrade.top/index.php?main_page=product_info&products_id=8117

The design of the hopper was modified to provide more room for the material transfer, without imposing any stresses on the auger. Fillets were added to the edges of the hopper to accommodate smoother material flow into the extruder. Supporting base was added to hopper system to provide additional support to the barrel.

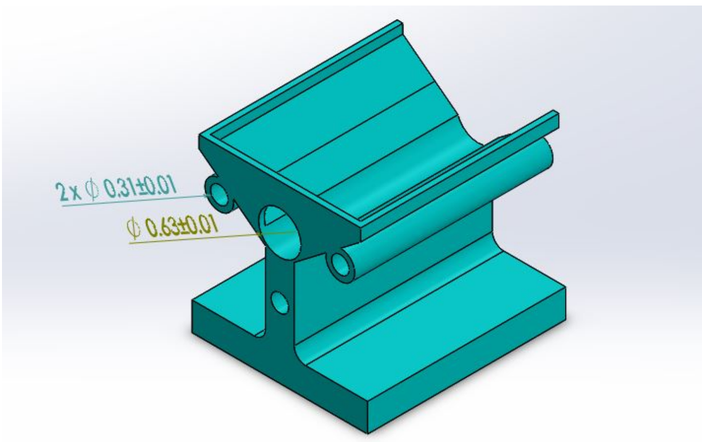


Figure 24 Redesigned Hopper with supporting base

3.2.2 Redesign of the transition zone:

The existing 12-inch long barrel was replaced with a 6-inch steel threaded pipe nipple. The length of the barrel was shortened to 6-inches to provide a better heat transfer and preheating of the material.

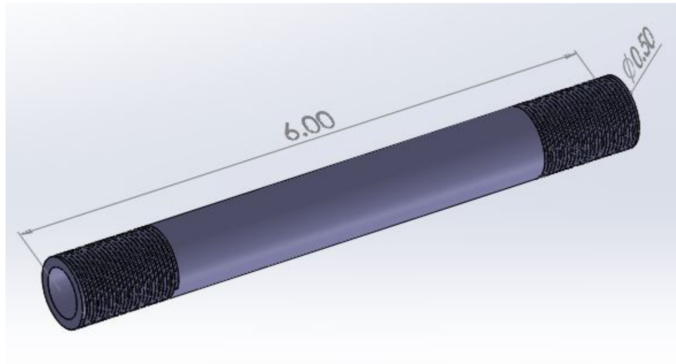


Figure 25 6-inch steel threaded pipe nipple

Two heating zones were introduced to the system to accommodate better transition of the material from solid form to molten form. Additionally, this reduces the load on the motor. Heating zone-1 is at the nozzle of the extruder, whereas heating zone-2 is placed at the middle of the barrel. Heating clamp with mineral insulation and heating tape were used to heat up the zone-1 and zone-2 respectively. Both the heating zones were controlled by PID controllers. The position of heating zones and the temperatures were set in such a manner that the temperature profile across the barrel is in incremental fashion, with the nozzle having the highest temperature. Care was taken to avoid the bridging phenomenon within the barrel.

3.2.3 Motor and Auger system:

The existing motor is replaced with a higher torque motor to withstand higher loading conditions. A 12 V DC motor with a starting torque of 640 in-oz and a full load current of 1.3 A was used for this purpose. The motor was connected to a stall protection board. Stall protection board is Pulse Width Modulation (PWM) controller that limits the current and prevents the motor from stalling.

Rated voltage (V)	No load		Rated load				Stalling condition	
	Current (mA)	Speed (RPM)	Current(mA)	Speed (RPM)	Torque(gf.cm)	Power output (W)	Max Torque(gm-cm)	Full load Current (A)
12	≤440	11	≤2050	8.8	480	17.8	47237	1

Table 3 Specifications of the motor

The motor-auger coupling system is modified with a keyed coupler to prevent the slippage of motor shaft under heavy loading conditions. The length of the coupler was increased from 0.75 inches to 1.5 inches to provide good support at the auger shank and eliminate any deflections at this point.

3.2.4 Additional supports to prevent deflections in the system:

A rectangular metal block was fixed at the end of the barrel flange. This block supports the weight of the auger as well as the barrel. It also accommodates a ball bearing and a self-lubricating sleeve system that supports the auger's rotation and prevents any kind of deflections in the auger.

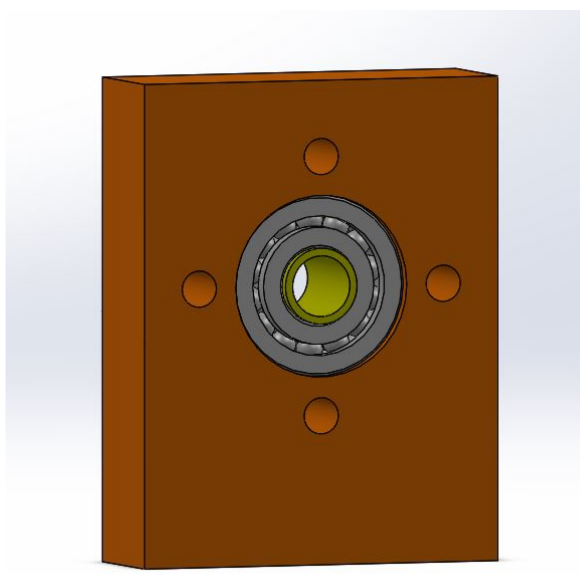


Figure 26 Rectangular block housing for ball bearing and self-lubricating sleeve

Three threaded rods were passed through the motor housing, rectangular block, barrel flange and the hopper to make sure the system is always aligned. These rods connect the rectangular block with the barrel flange, which supports the barrel on flanged end. The nozzle end of the barrel was fixed with bell hanger caddy for the support. These supports on both ends of the barrel prevent any kind of deflections in the barrel.

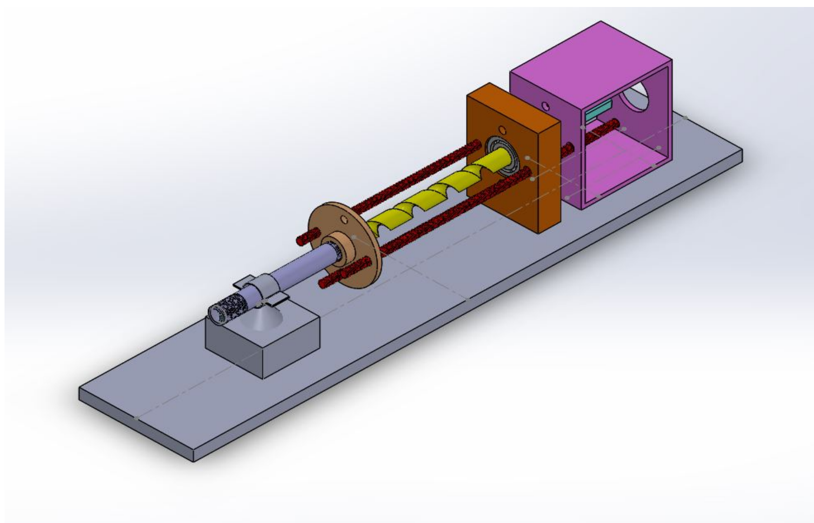


Figure 27 Final assembly of the system

3.2.5 Electronics and electrical connections:

Most of the electronic and electrical connections were taken from the Filastruder's design.

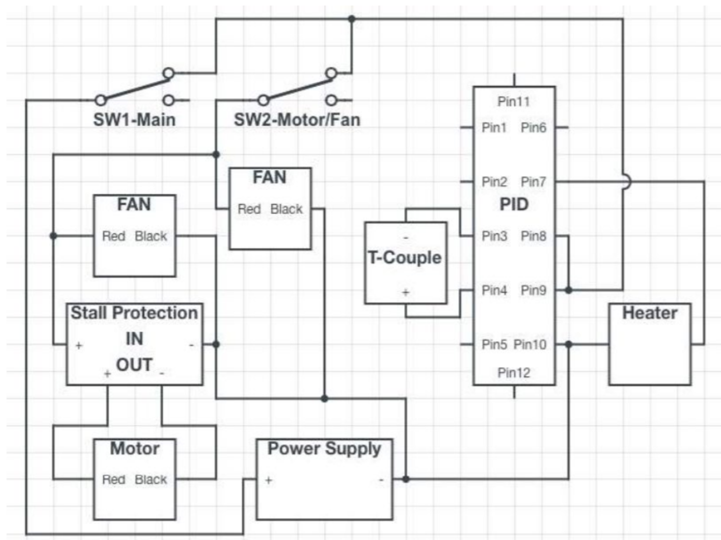


Figure 28 Electric and Electronic Connections of Filament Extruder

Source: www.filastruder.com

4.METHODOLOGY

The goal of this study is to investigate the mechanical behavior of 3D printed ABS polymer when subjected to multiple recycling cycles. This study is conducted in two parts. In the first one, a batch of virgin ABS material is taken, recycled multiple number of times until it is no longer printable. In the second part, this resulting recyclate is blended with virgin ABS at various proportions and the properties are studied.

4.1. Recycling of virgin ABS

The input material for this study is a commercial ABS filament – AmazonBasics ABS 3D printer filament. Initially, a batch of 10 samples were printed with this filament and tested for tensile properties. This batch of material is recycled and is used for further generations in the study. One generation of recycling and testing consists of the following steps:

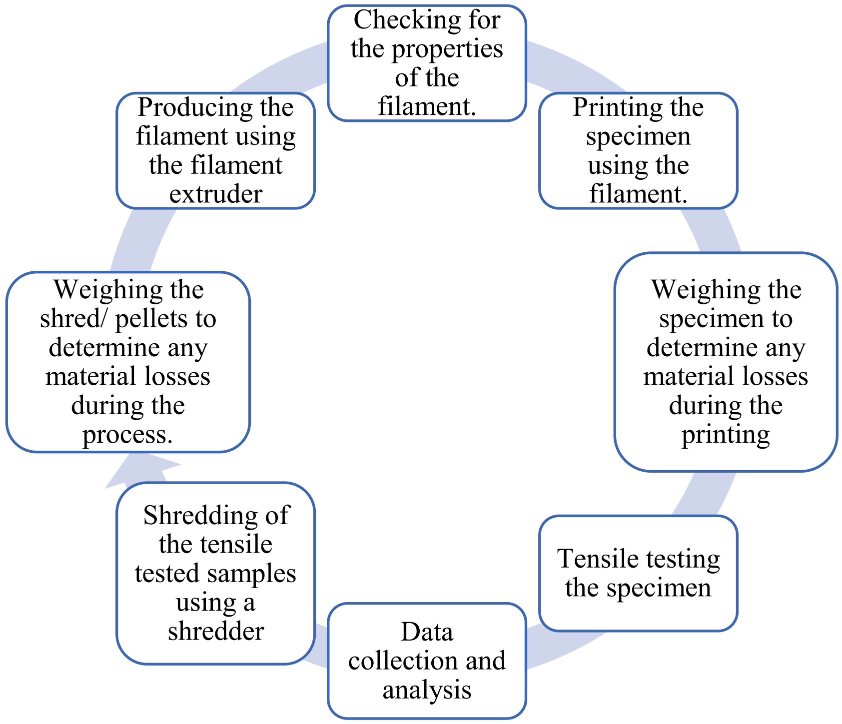


Figure 29 Recycling process of one cycle

4.1.1. Shredding of the tensile test samples into pellets.

The specimens after the tensile test are shredded using a commercially available micro-cut shredder. The shredder used for this purpose is GoECO Life GMW 101P micro-cut shredder. The specimens are fed into the shredder and reduced to the size of 5×10 mm on average. This shred is used as pellets/ feedstock for the filament extruder.

4.1.2. Weighing the shred/ pellets to determine any material losses during the process.

The batch of shredded material is weighed on milligram sensitive weighing scale to determine any losses that may have occurred during the shredding process. The losses at this level could be because of the following reasons –

1. Material getting stuck in the teeth of the shredder blades.

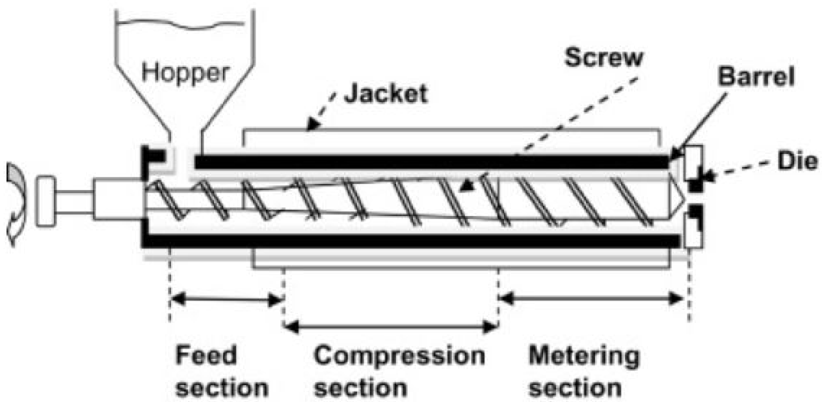
2. Material getting shred to a very fine size, resulting on collection and transfer losses before the extrusion process.

4.1.3. Filament Extrusion

A single screw filament extruder is used to produce a filament of 1.75mm diameter from the shredded material. The material must go through the three processing zones in the filament extruder.

1. Feed / solid conveying zone – In this zone the material is collected from the hopper and is conveyed further to the transition zone. If there are any bigger pellets present in the material, they get shredded to a finer size in this zone. The material is preheated towards the end of this zone.
2. Transition zone – In this zone the material is subjected to controlled heating and starts to soften down. This zone contains a mixture of solid pellets and melted plastic. A change in density of the material is observed here.
3. Metering zone – The material is exposed to even higher temperatures here. The material is totally melted and melt pool is formed in this zone. A change in

density and viscosity of the material is observed here. Towards the end of this zone, the material is pushed through the die to take the shape of the filament. The extrusion speed of the filament is monitored for every reprocessing cycle and the temperature of the two heating zones in the extruder is adjusted accordingly.



Source: https://www.sciencedirect.com/topics/engineering/single-screw-extruder

Figure 30 Schematic representation of different zones in a single screw extruder

4.1.4. Cooling down the filament through the guide ways

After the filament is extruded, it is passed through guide ways, to avoid any kind of kinks in the filament. During this process, the filament is cooled using two 12 volt- 60mm fans from above to enhance solidification. The fans are controlled using a PWD controller.

4.1.5. Spooling of the filament

The filament is then spooled using a filament winder. The winder pulls the filament from the nozzle through the guideways. The speed and direction of the winder are controlled using a servo motor and controller set. The diameter of the filament is affected by the speed of the filament winder. So, by monitoring the filament's diameter, the winder is set at a speed where a filament with consistent diameter of 1.75mm is extruded. The spooled filament is used as a feedstock for the 3D printer to print a next generation of tensile test specimens.

4.1.6. Checking for the properties of the filament:

4.1.6.1. Diameter of the filament: After The filament is extruded, it is checked for the consistency in the diameter throughout its length. For this, filament of length one feet is marked and cut at every inch. On every part, the diameter of filament is measured, using a Vernier calipers, at three places and the average is noted.

4.1.6.2. Weight of the filament: Similar to the check for diametrical consistency, the weight of the filament is also checked for the consistency. Each piece of the cut filament from the above test is weighed on a milli-gram sensitive weighing scale. Along with this, the weight of the entire filament produced is also noted in milligrams.

4.1.7. Printing the specimen using the filament.

The extruded filament is loaded into the Makerbot Replicator 2X printer for printing the tensile test specimens. ASTMD638-Type-I tensile bar geometry is employed in this study. ASTMD638-I tensile bars are used for testing the tensile properties of plastics (both reinforced and unreinforced). The geometry of the specimen is shown in the table-

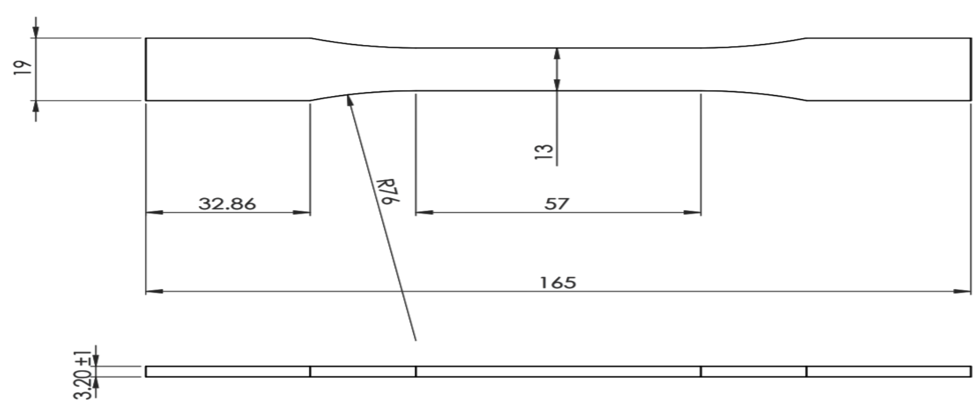
ASTM D638-Type-I

All the dimensions are in mm.

Figure 31 ASTM D638 Type-1 Specifications

The specimen is designed using Solidworks software and is converted to an STL file. Later this STL is sliced up using MakerBot's slicing software. The temperature of the extruder's print head is maintained at 230 C and the print bed temperature is set at 110 C for the first generation. However, the printing parameters are varied based on printing behavior and are noted for every reprocessing cycle.

Terminology used to describe the printing outcomes in this study –

In order to identify and categorize the printing outcomes from each cycle, we employed the following terminology and defined them as per our requirement. It is to be noted that these definitions are confined only to this study.

Successful Prints – this includes when the specimen is printed completely from first layer to the last, without any voids in between. In addition to that, it includes when there is enough adhesion in between the layers to keep the specimen intact for testing.

Failed Prints – this includes the specimen that has any kind of voids present in between its layers. It includes incomplete prints which can occur when the printer stops extruding any material. It also includes specimens with poor layer to layer adhesion.

Successful Prints	**Failed Prints**
No voids	Voids are present
Complete prints	Incomplete prints
Sufficient layer-to-layer adhesion	Poor layer-to-layer adhesion

Table 4 Table representing the definitions of successful prints and failed prints

4.1.8. Weighing the specimen to determine any material losses during the printing.

In this step, after printing the specimen, each of them, as well as the whole batch of specimens are weighed using a milligram sensitive weighing scale. By comparing the weight of whole batch of specimen to the recorded weight of the filament, any loss of material during the printing process can be determined.

4.1.9. Tensile test of the specimen.

To study the tensile properties of the specimens, tensile tests using the, Psylotech's "Modular under Microscope Mechanical Test system - μTS" are conducted. It is shown in the picture (3.1) below. Displacement controlled tensile tests were conducted. In this type of tensile tests, a known displacement (δL) is applied at a uniform rate and the corresponding loads are noted. Here a displacement of 10 mm is applied at a uniform rate of 50μm/sec and the load (F) is noted at a time interval of 0.10 sec. The obtained load is used to calculate the stress (σ) at corresponding cross-sectional area (A) and displacements are used to calculate strains.

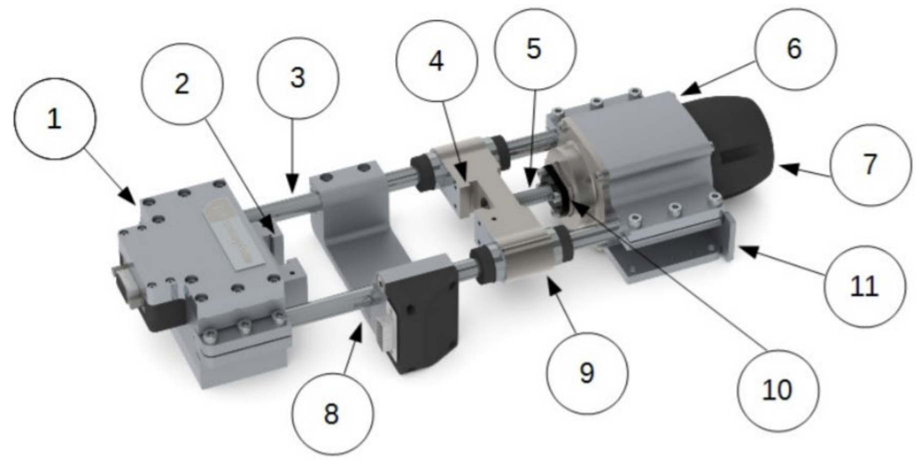


Figure 1.1 μTS Test Frame, 1. Fixed Crosshead and Load Cell, 2. Fixed Grip Mount, 3. Support Shaft, 4. Moving Grip Mount 5. Ball Screw, 6. Actuator Housing, 7. Rotary Encoder, 8. Local Displacement Sensor 9. Moving Crosshead 10. Ball Nut, 11. Cable Egress

Figure 32 Tensile test frame used for testing

Source: Psylotech μTS User Manual, December 2017

The stress strain calculations are as follows-

$$Stress\ (\sigma) = \frac{F}{CSA}$$

Equation 2

F = Load applied on the specimen (N)

CSA – cross sectional area of the ASTM-D638-I specimen = 41.6 mm

$$Strain\ (\varepsilon) = \frac{\delta L}{L}$$

Equation 3

δL = change or displacement in the gauge length of the specimen (mm)

L = gauge length of the specimen (mm)

With the obtained values, stress strain curves are plotted, and the nature of the curves are studied.

Effective Modulus is calculated for each specimen.

$$E_{effective} = \left(\frac{\sigma}{\varepsilon}\right)_{effective} \qquad \text{Equation 4}$$

4.2. Blends of virgin and recycled ABS:

Initial batch of ABS material was recycled until it was totally degraded and can be no longer used for 3D printing. Total degradation in the material was observed in the 5th reprocessing cycle. During this cycle, black specs were observed on the filament indicating a degradation in the material. After the extrusion, spooling of the filament became impossible because of the increased brittleness in the material. In addition to this, when the material was fed into the printer, the filament was ground up into powder and could not be extruded through the printer's nozzle.

In order to study how the material behaves when blended with virgin ABS, the resulting shredded recyclate after the 5th cycle is blended with commercially available ABS pellets at various proportions. This mixture is then extruded into a filament and is printed into tensile test specimens. These specimens were tested for tensile test properties. With the obtained results stress strain curves were plotted and studied.

The proportions were started with 70% recyclate and 30% virgin ABS. A printing failure was observed with this combination. So, the percentage of the recycled material was further reduced in rest of the combinations. The results of various combinations are as follows-

R \ V	30 %	40 %	50 %	60 %	70 %	80 %	90 %
10 %							S
20 %						S	
30 %					S		
40 %				S			
50 %			F				
60 %		F					
70 %	F						
V – Virgin ABS R – Recycled ABS (recyclate after the 5^{th} reprocessing cycle)			F – Failed prints S - Successful prints				

Table 5 Print success-failure matrix for different blends of ABS

4.2.1. Recycling of the V-R blends

After the blends were tested for the tensile properties, they are further recycled to study their behavior when subjected to recycling. For this purpose, the blends of 70% Virgin – 30% Recycled, 80% Virgin – 20% Recyclate and 90% Virgin – 10% Recyclate were considered. The tensile test specimens of the blends were shredded, extruded and 3D printed similar to process described in the section 3.1.

	70%V-30%R	80V%-30R%	90%V-10%R
Cycle 1	F	S	S
Cycle 2	F	S	S
Cycle 3	F	F	F

Table 6 Print success failure matrix for different recycling cycle of the blends

The printed specimens were tested for the tensile properties. With the obtained results, stress strain curves were plotted. They were used to study the mechanical behavior of the recycled virgin ABS-recyclate blends.

Chapter 5

Results and Discussions

This chapter is divided into 4 sections, detailing the results of our recycling experiments. These sections include-

- Multiple Recycling cycles of virgin ABS (5.1);
- Recycling of Blends of virgin-recycled ABS (5.2);
- Recovery of the properties in recycled ABS (5.3); and
- Multiple Recycling cycles of the virgin-recycled ABS blends (5.4).

5.1 Multiple recycling cycles of virgin ABS

In this part of study, a batch of virgin ABS material was processed multiple number of times until the material degraded and was no longer printable. It was observed that the material was not printable after the 5th reprocessing cycle.

5.1.1 Tensile tests

Each printed specimen was tested for the tensile properties. From the load and displacement data that was taken from each test, ultimate tensile strength, elongation at break (%) and Young's modulus were calculated and plotted. The specimens are tested with a displacement of 10mm at a velocity 50 μm/s.

A. Cycle -1:

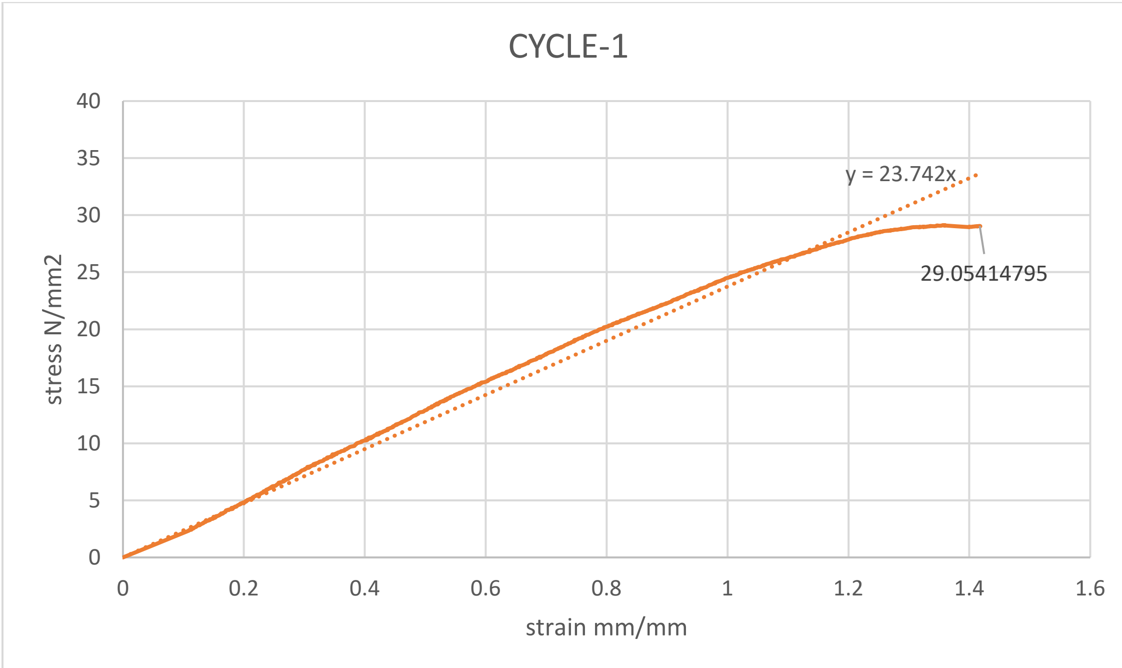


Figure 33 Stress Strain Curve of cycle-1

A batch of 10 dog bone samples, 3D printed from virgin ABS were tested in this experiment. Force and displacement data for each sample was obtained from the test and stress and strains were calculated with that data. A stress-strain curve was plotted from the average stresses and strains obtained from the 10 samples. An ultimate tensile strength (UTS) of 29.121 MPa at 1.35% strain was observed from the test. The specimen broke at 1.48% strain. A linear gradient of the curve was plotted in order to determine the Young's Modulus of the material, which was 22.63 MPa for cycle 1. In this cycle, the total number of thermal cycles that the material underwent is 2; one from extrusion and the other from 3D printing.

B. Cycle -2:

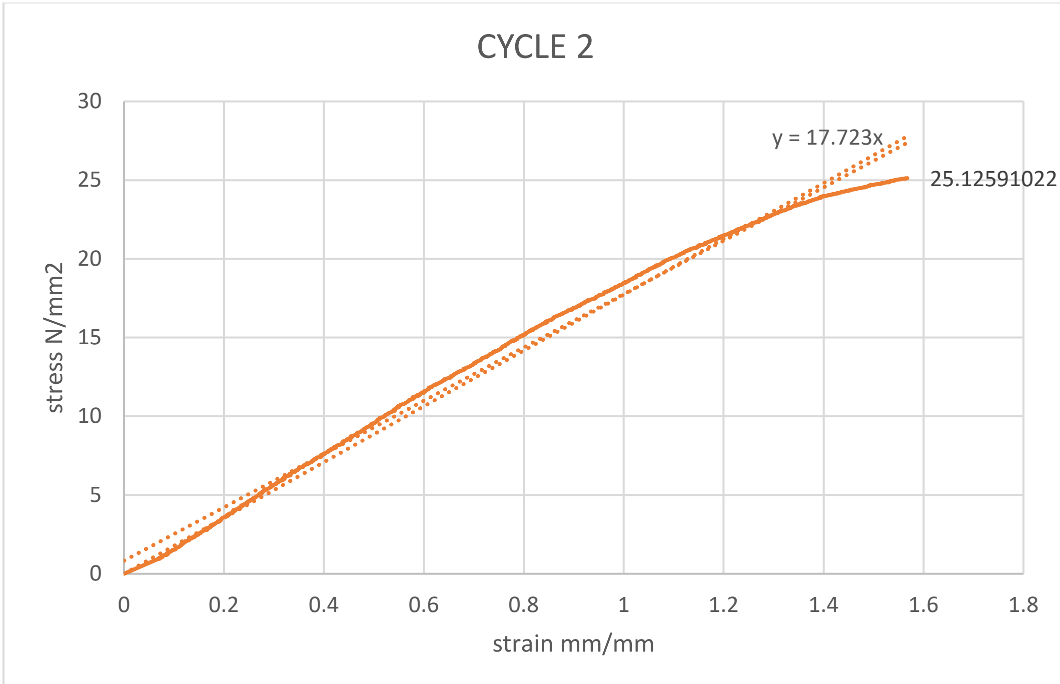


Figure 34 Stress Strain Curve of cycle-2

After the recycling the cycle 1 samples, the material was used in 3D printing the tensile test specimens for cycle 2. From the obtained results, it is observed that the material's ultimate tensile strength (UTS) decreased to 25.125 MPa at 1.56% strain, accounting for up to 13.72% decrease in its UTS, when compared to virgin ABS. A significant decrease in Young's Modulus by 25% was observed. The total number of thermal cycles that the material underwent is 4.

C. Cycle- 3:

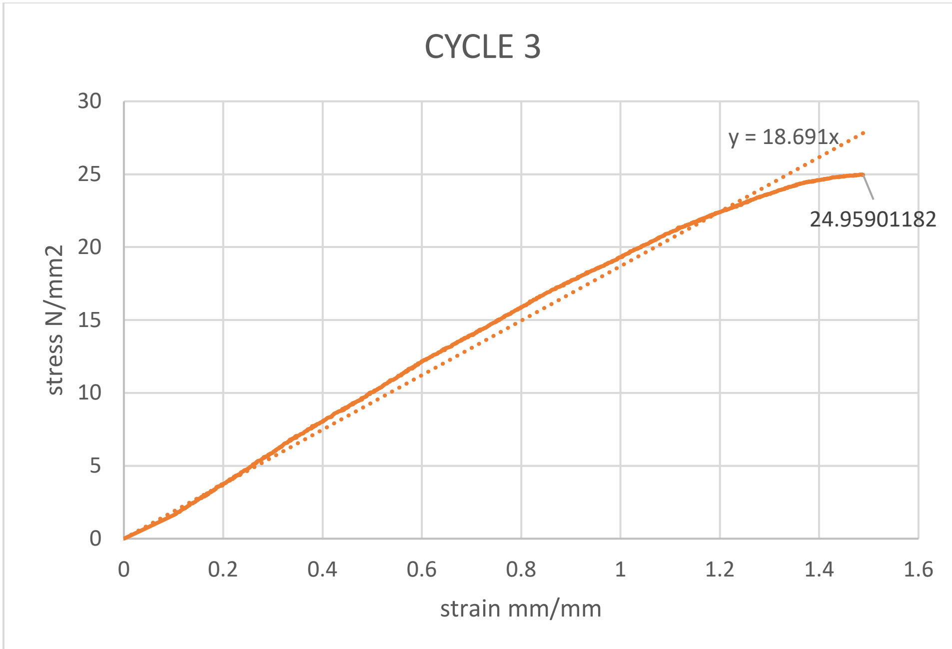


Figure 35 Stress Strain Curve of cycle-3

The samples from cycle 2 are recycled to 3D print another set of dog bone tensile test specimen. From the obtained values, it is observed that the ultimate tensile strength of the material is not affected further by the 3rd recycling cycle. However, there has been a 5% increase in the Young's modulus, when compared to cycle 2.

D. Cycle -4:

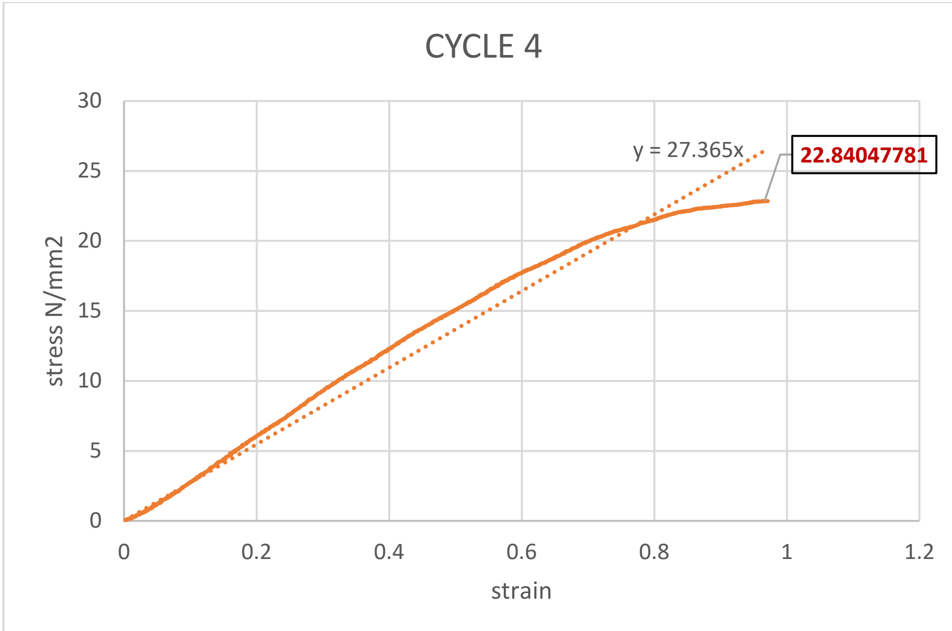


Figure 36 Stress Strain Curve of cycle-4

When the material from the previous cycle was processed into a filament, very small black dots were observed on filament surface. These dots indicate a degradation in the material. From the data obtained from the tensile tests, it is observed that the ultimate tensile strength of the material is decreased to 22.85 MPa at 0.96% strain. This indicates a 21.52% of decrease in the ultimate tensile strength when compared to virgin ABS. In addition to that, the Young's modulus of the material increased to 25.402 MPa, which is almost equal to that of the virgin ABS.

E. Cycle-5

In this generation, when the material was recycled and extruded, a change in the color of filament from white to light grey was observed. The material showed an increased brittle behavior, which made it difficult to spool the filament. So, the filament was extruded and guided manually. When the filament was used for 3D printing, the filament was grounded and powdered in between the feeding gears, resulting in printing failure. This is due to the increased brittleness of the material. As a result, the material was not extruded from the nozzle and this concludes that the material is no longer printable.

5.1.2 Influence of cycle number on the properties

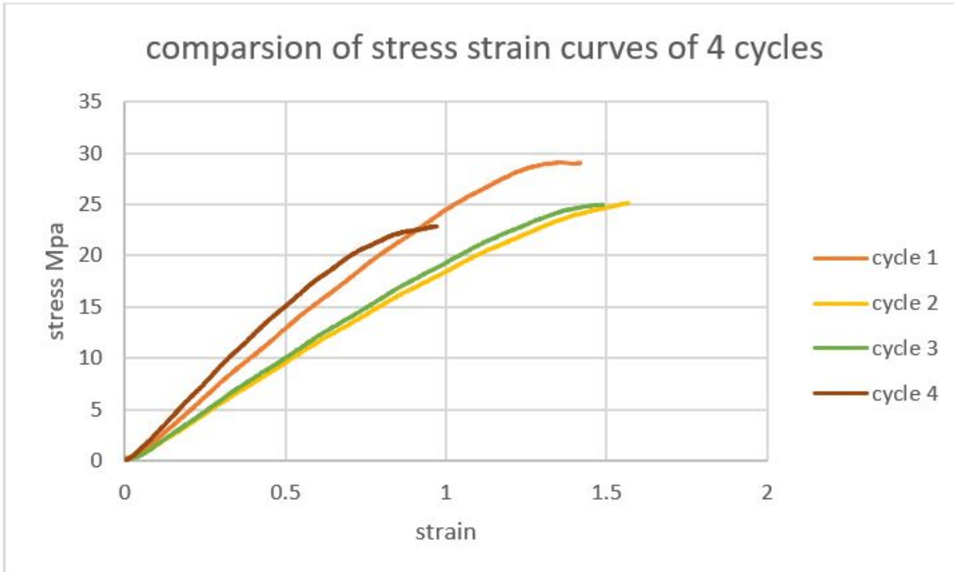


Figure 37 Stress strain curves of four cycles

All the stress strain curves of the four cycles were plotted together for a better understanding of behavior of the material, when subjected to recycling.

Cycle Number	1	2	3	4	5
Ultimate Tensile Strength (σ_{ut}) MPa	29.121	25.125	24.9793	22.8539	Printing failure
Ultimate Strain (ε_u %)	1.3570	1.5675	1.4822	0.9638	Printing failure
Elongation at Break (EB%)	1.4181	1.5675	1.4860	0.9712	Printing failure
Young's Modulus (E) GPa	23.74	17.722	18.68	27.36	Printing failure
Number of samples	10	9	9	8	Printing failure
Thermal cycles	2	4	6	8	9

Table 7 Mechanical properties of ABS for multiple recycling cycles

From the obtained data it can be observed that the ultimate tensile strength (UTS) of the material reduced with the increase in number of recycling cycles. Though, a significant change in the properties is observed in the cycle 2, the material showed similar behavior in cycles 2 and 3. An increase of 39.60% in the Young's modulus is observed in cycle 4. Although, this value is almost equal to that of virgin ABS, a decrease in its ultimate strain and elongation at break implies the increase in brittleness of the material. This phenomenon explains why the material in the 5th cycle is highly brittle and is no longer printable.

One sample each from cycles 2 and 3 are eliminated because of the slippage during tensile testing. In the fourth cycle, two of the samples were eliminated because of the printing failures.

For every reprocessing cycle, the material undergoes two thermal cycles, one from the filament extrusion process and the other from the 3D printing extrusion process. But for the fifth cycle, as the material was not processed through the 3D printer, the corresponding thermal cycle was eliminated.

The highest and the lowest values of each property were highlighted in the table with red and yellow colors respectively.

A. Ultimate Tensile Strength

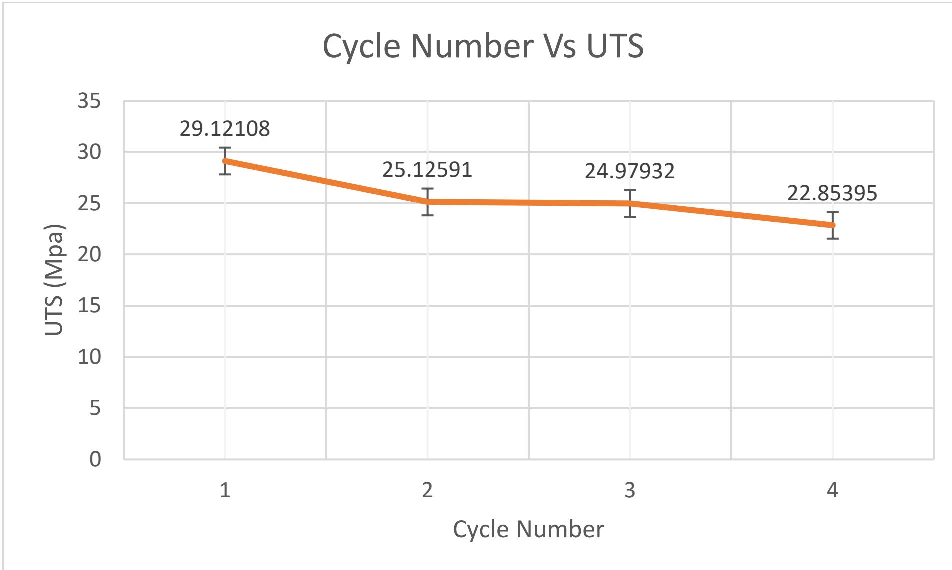


Figure 38 Ultimate tensile strength Vs Cycle Number - Four Cycles

This graph shows the trend of UTS with respect to the cycle number. As mentioned earlier, a significant decrease can be observed from cycle 1 to cycle 2 and cycle 3 to cycle 4.

B. Ultimate Strain

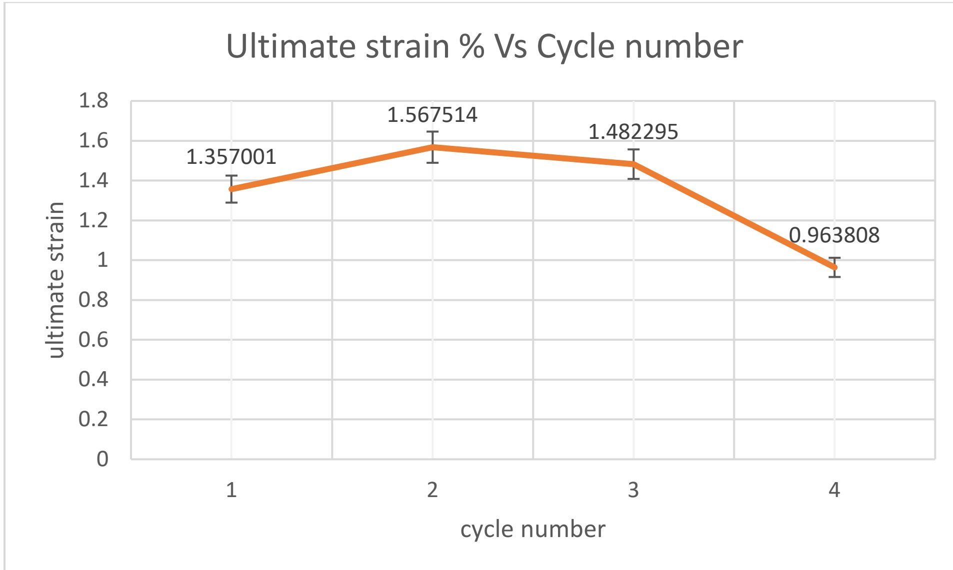


Figure 39 Ultimate strain Vs Cycle Number - Four Cycles

The above graph shows the trend of the ultimate strain with respect to the cycle number. As you can see, the material did not show much variation in the ultimate strain in the first three cycles, but there has been a sudden drop of 28.89% in it, in the 4th cycle.

C. Elongation at break

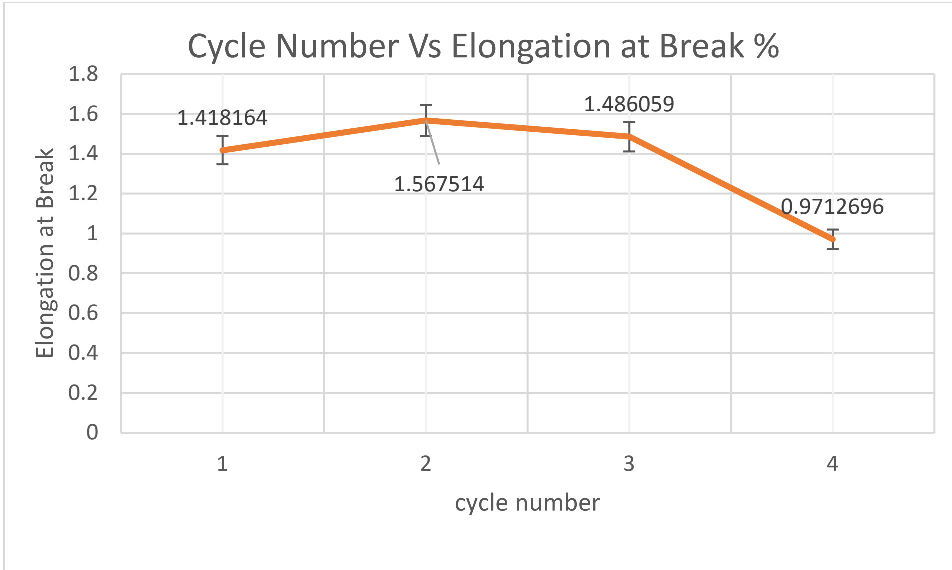


Figure 40 Elongation at Break Vs Cycle Number - Four Cycles

Graph shows the variation of elongation at break with respect to the cycle number. Elongation at break followed the similar trend as the ultimate strain. Though, elongation at break did not show much variation in the first 3 cycles, it suddenly decreased by 31.50% when compared to virgin ABS.

D. Young’s Modulus

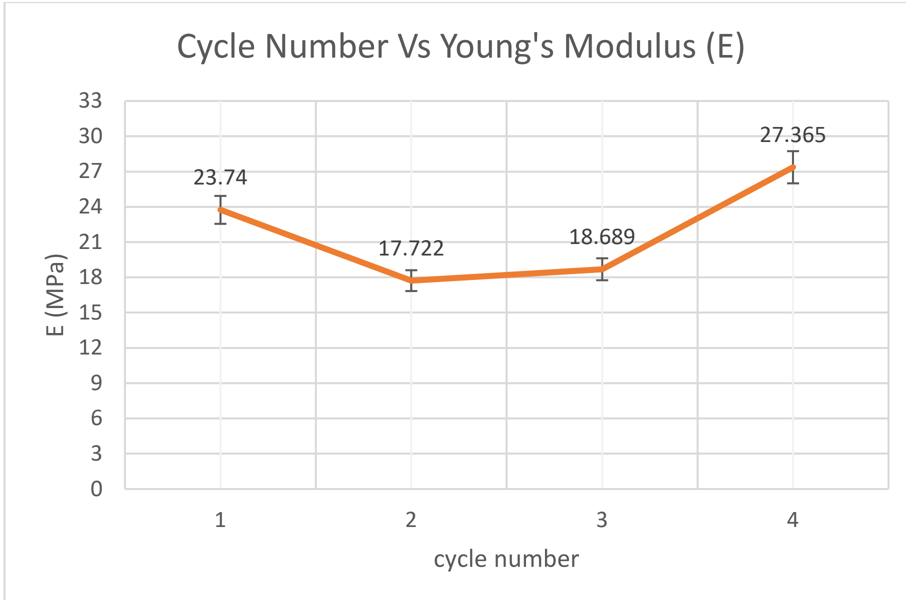
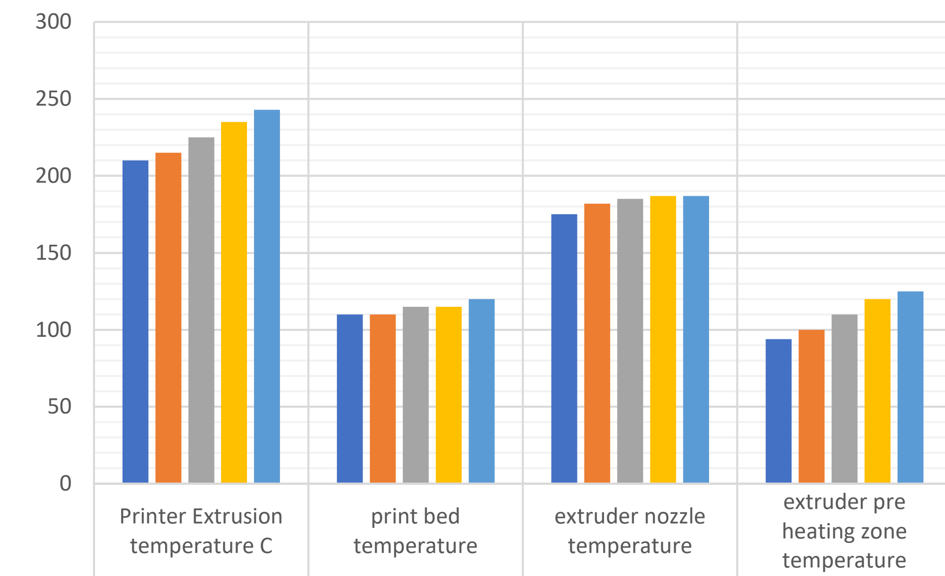


Figure 41 Young's Modulus Vs Cycle Number - Four cycles

The above graph explains the variation of Young’s modulus with respect to the cycle number. The Young’s modulus of the material decreased by 25.13% from cycle 1 to cycle 2. There was no significant variation from cycle 2 to cycle 3. However, it increased by 41.6% from cycle 3 to cycle 4. This behavior of the material explains the onset of brittle nature in cycles 4 and 5.

5.1.3 Temperatures of the extruder and printer



	Printer Extrusion temperature C	print bed temperature	extruder nozzle temperature	extruder pre heating zone temperature
cycle 1 (V)	210	110	175	94
cycle 2	215	110	182	100
cycle 3	225	115	185	110
cycle 4	235	115	187	120
cycle 5	243	120	187	125

cycle 1 (V) cycle 2 cycle 3 cycle 4 cycle 5

Figure 42 Temperatures of Extruder and Printer for Every Cycle

The temperatures of the 3D printer extruder head, print bed, filament extruder nozzle and extruder preheating zone were for every recycling cycle. The reason for this variation in the filament extruder is to maintain a constant extrusion rate of 10 inch/min for every cycle. However, this variation in temperatures resulted in a particular trend when compared with cycle number. With the increase in the cycle number, an increase in the processing temperatures of the extruder is observed. This indicates that because of the repeated processing of this material, the material's melt flow index (MFI) has decreased.

5.2 Blends of Virgin and Recycled ABS

In this section of the study, the recycled material from the fifth cycle was blended with virgin ABS material at various percentages. The purpose of this experiment is to determine if we can recover any of the properties of the recycled ABS by blending with fresh (virgin) material. The blends were varied from in the following sequence-

Blending ratio	70R-30V	60R-40V	50R-50V	40R-60V	30R-70V	20R-80V	10R-90V
F/S	F	F	F	S	S	S	S

Table 8 Print success- failure matrix for different blend

Here **V** stands for the percentage of virgin ABS present in the combination, **R** for the percentage recyclate material in the combination, **F** represents the printing failure of the material whereas **S** represents the successful printing of the material. It can be seen from the table, that any combinations that had more than 50% recycled material, resulted in the printing failures. All the filaments within these combinations were very brittle. When we tried to 3D print with these filaments, they fragmented in the extruder head, resulting in a printing failure.

The blends with less than 50% of the recycled ABS, exhibited less brittle behavior when compared to the ones with higher recycled material content. These filaments were able to pass through the feeder gears, without fracturing. Thus, they resulted in successful prints. These dog bone 3D printed specimens were tested for the tensile properties and were further analyzed.

5.2.1 R (60V-40R)

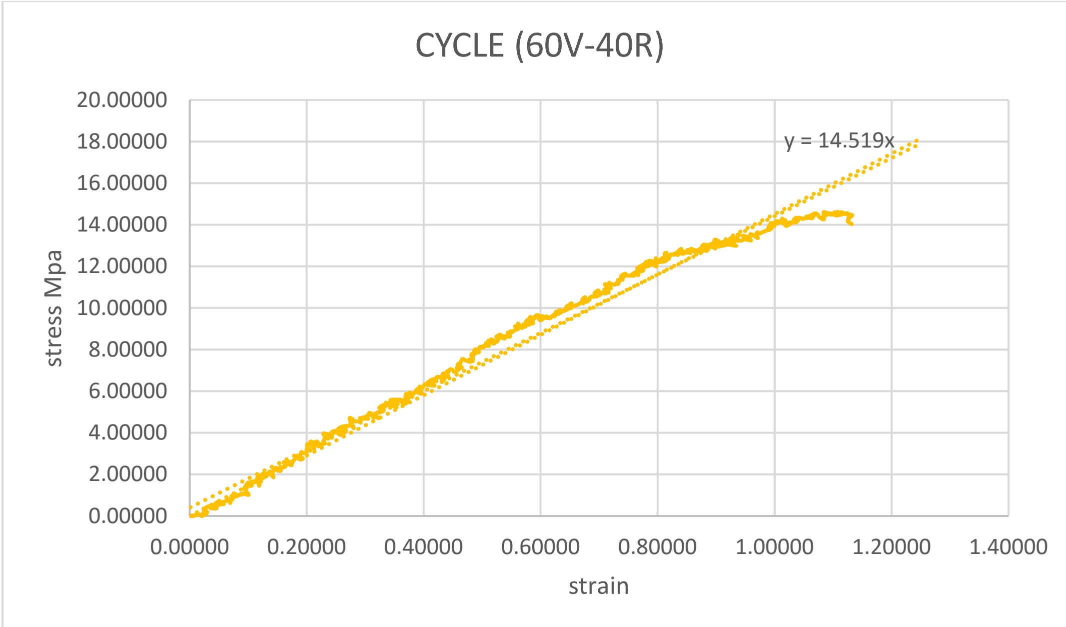


Figure 43 Stress strain curve of Cycle R(60V-40R)

The material was manually blended and then extruded. However, the material was still brittle, which made it difficult to spool. Sufficient material for 3 samples were initially prepared. But, only one out of the three samples were printed completely. The rest of the two prints showed incomplete adhesion between the layers, resulting in a failed print.

Thus, the test was carried out with a single sample and the properties were analyzed. From the graph it can be observed that the ultimate tensile strength of the material is 14.62 MPa at a strain of 1.132%

5.2.2 R (70V-30R)

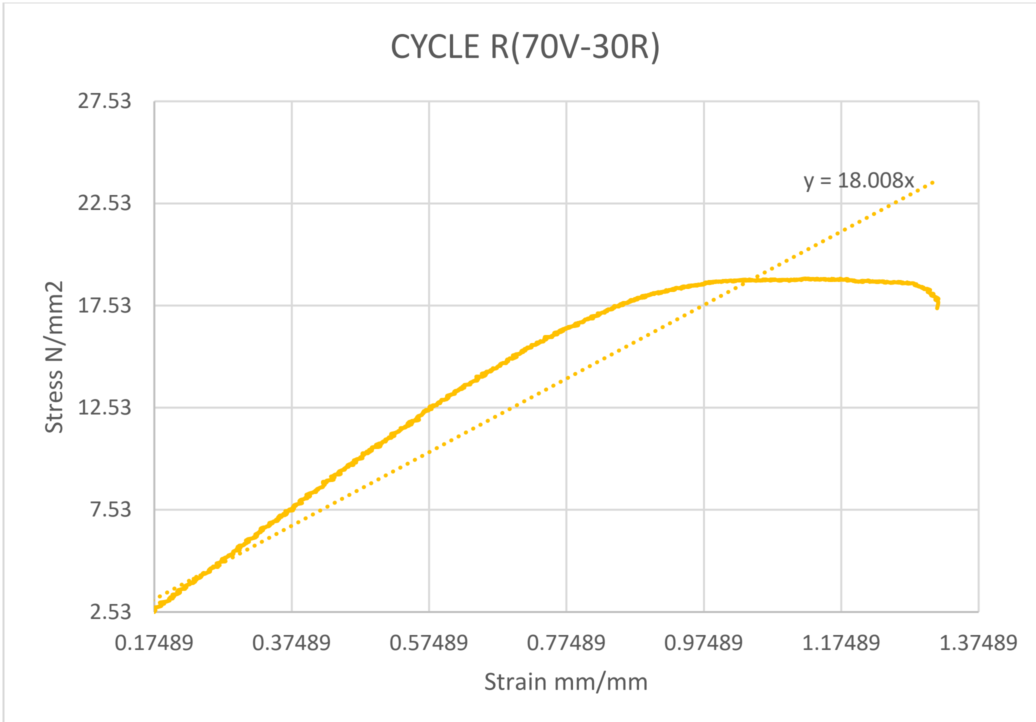


Figure 44 Stress strain curve of Cycle R(70V-30R)

This blend was prepared in the similar fashion as the 60V- 40R. This blend resulted in the successful prints for testing. From the above graph, it can be observed that the UTS of the material is 18.85 MPa at 1.2% strain, which is 35.26% less than the virgin ABS. Even though the material was blended with virgin ABS, its UTS was further decreased when compared to cycle 4. This must be because of the further degradation of the recyclate portion present in the blend. However, a significant improvement of 34.96% in the Young's modulus is observed in this cycle, when compared to cycle 4. The figures show that the Young's modulus of the material in this blend is almost equal to the Young's modulus of cycles 2 and 3. Crazing in the tensile test specimen also was observed in this batch of experiments.

5.2.3 R (80V-20R)

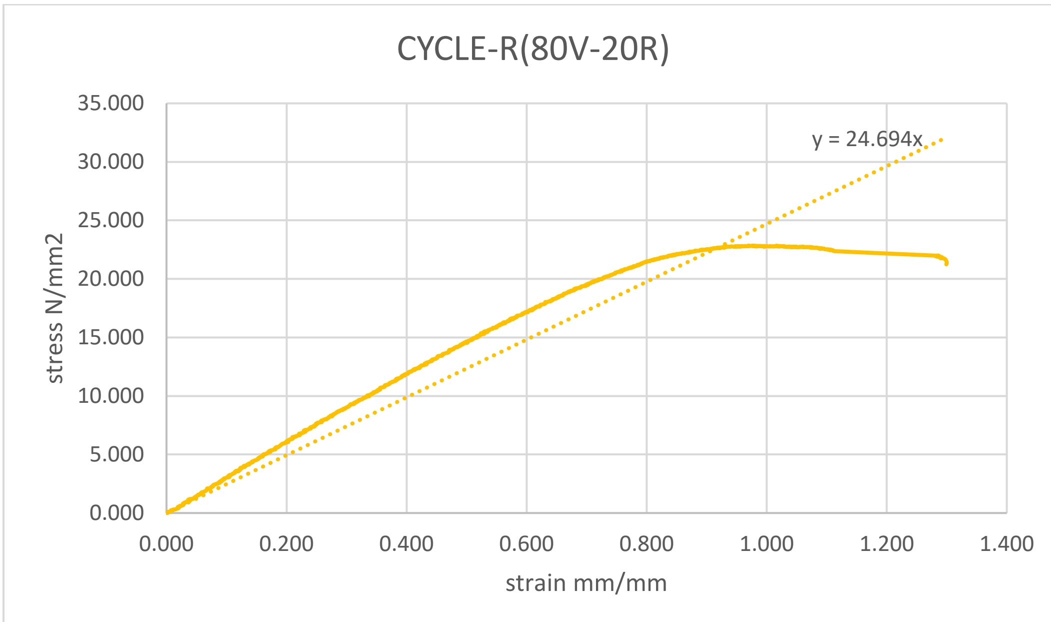


Figure 45 Stress strain curve of Cycle R(80V-20R)

From the graph, it can be observed that the ultimate tensile strength (UTS) of this material is 22.83 MPa at a strain of 0.97%. This is 27.11% less than that of virgin ABS. Elongation at break is at 1.2%. This difference in the both the strains and the plotted curve, indicates the onset of plastic behavior in the material.

5.2.4 R (90V-10R)

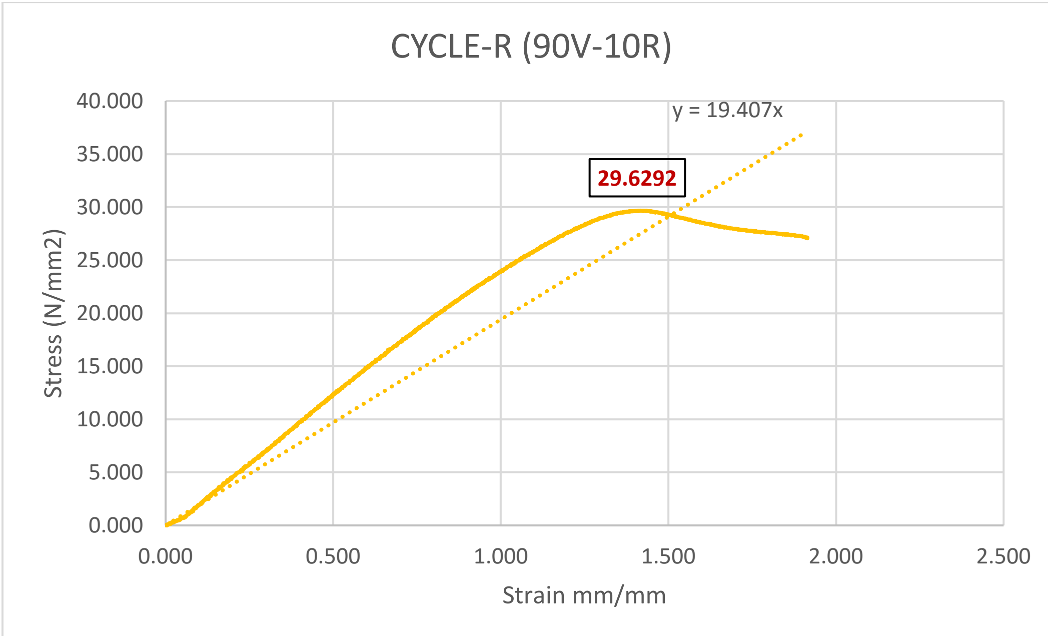


Figure 46 Stress strain curve of Cycle R(90V-10R)

In this blend, 90% of the material is virgin ABS, whereas the remaining 10% is recycled. According to the results, the ultimate tensile strength of the material is 29.67 MPa at a strain of 1.41%. This value is almost equal to that of the virgin ABS. The elongation at break for this batch is 1.91% which is greater than virgin ABS by 0.5%. These figures indicate the recovery of the tensile properties in the sample.

5.2.5 Influence of blending ratio on the properties

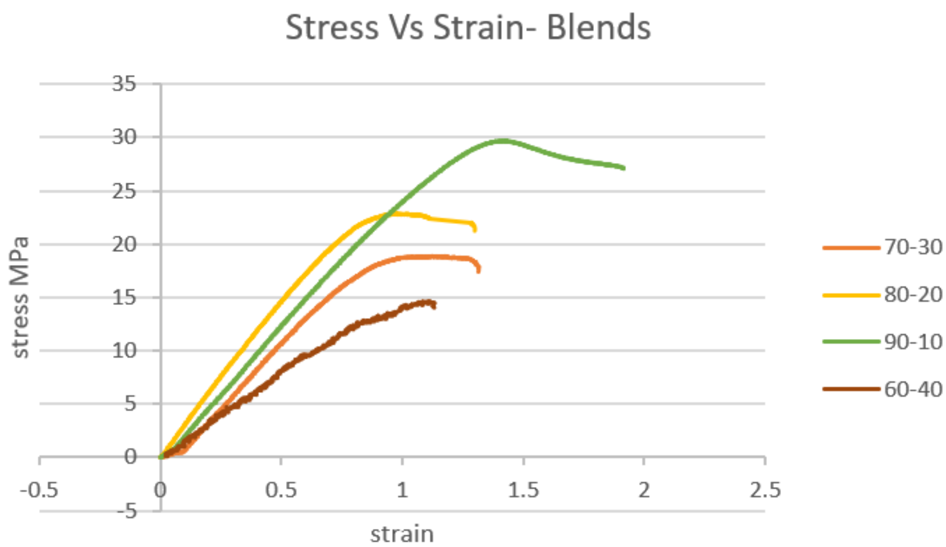


Figure 47 Stress strain curves of blends

All the stress strain curves of the four cycles were plotted together for a better understanding of behavior of the material, when subjected to recycling.

Blending Ratio V-R	60V-40R		70V-30R		80V-20R		90V-10R	
Ultimate Tensile Strength (σut) MPa	14.62		18.85161		22.83782		29.6739	
Ultimate Strain (εu %)	1.129		1.21322		0.97046		1.417	
Elongation at Break (EB%)	1.130		1.31443		1.299207		1.9145	
Young's Modulus (E) GPa	14.519		17.99		24.694		19.407	
Thermal Cycles (V|R)	2	11	2	11	2	11	2	11

Table 9 Mechanical properties of different V-R blends of ABS

From the obtained data it is observed that the UTS of the material increased with the increasing percentage of the virgin ABS. In addition to that, a raise of 46.2% in the ultimate strain and a drop of 24.01% in the Young's modulus is observed from cycle 70V-30R to cycle 90V-10R. These values project the improvement of ductile properties in the recyclate material. Also, as the figures of cycle 90V-10R indicate that the properties are similar to that of virgin ABS, it can be concluded that the losses occurred due to the recycling can be restored with the addition of 90% of virgin ABS.

In this section, the total number of thermal cycles that the virgin and recyclate parts of blend have gone through is 2. However, the recyclate has already undergone 9 thermal cycles from the previous section, accounting it to a total of 11 in this section.

A. Ultimate Tensile Strength

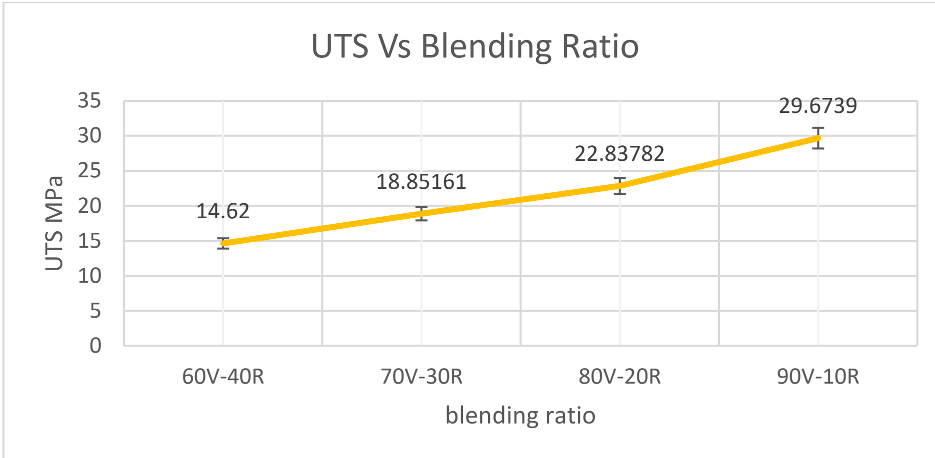


Figure 48 Influence of Blending Ratio on UTS

This graph shows the how the UTS of the material varied with the different blending ratios. From the data, it is evident that the Ultimate Tensile Strength of the material increased with the increasing content of virgin ABS.

B. Ultimate Strain

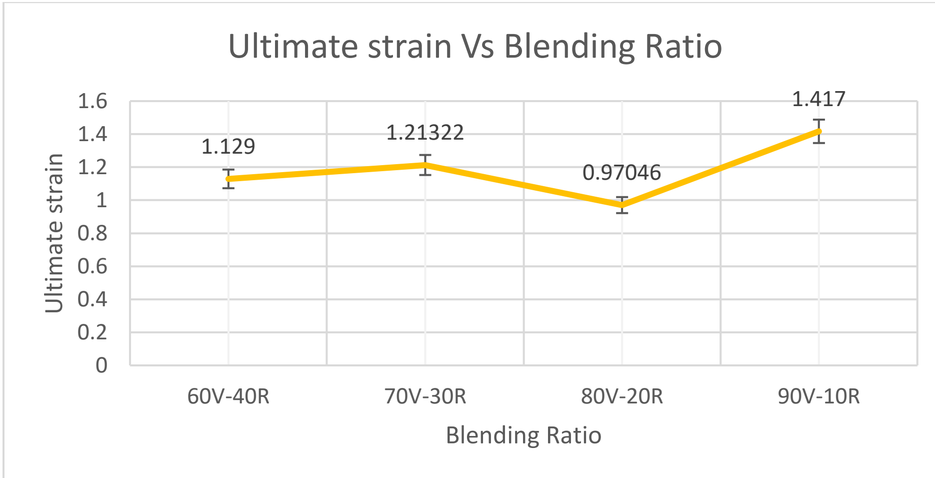


Figure 49 Influence of Blending Ratio on Ultimate strain

This graph shows the how the ultimate strain of the material varied with the different blending ratios. From the data, it is evident that, in the overall sense, the ultimate strain of the material exhibited an increasing trend from 60V-40R to 90V-10R. However, there was no variation in the ultimate strain of the material when the virgin content was varied from 60% to 70%. A slight dip in curve was observed at the cycle 80V-20R and it increased by 44% at cycle 90V-10R

C. Elongation at Break

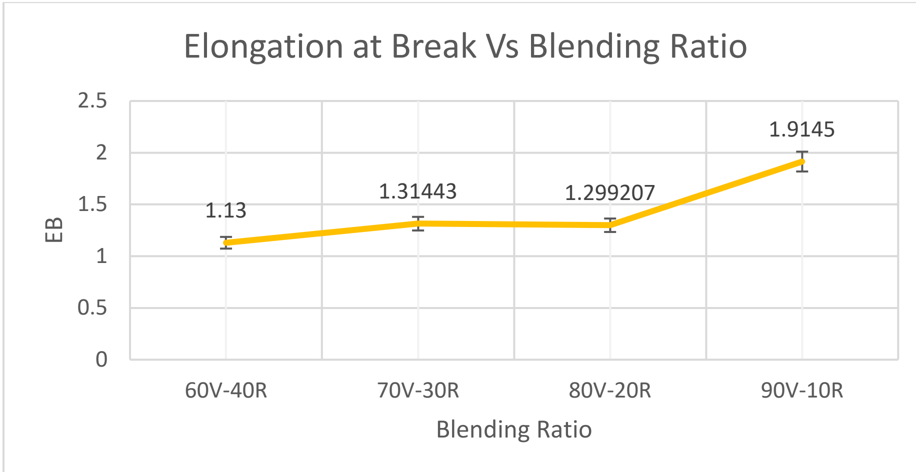


Figure 50 Influence of Blending Ratio on Elongation at Break

This graph shows the effect of blending ratio on the % elongation at break of the material. From the data, it can be observed that the blending ratio did not have significant effect on failure strain of the material in the first three combinations. But, when 90% of the virgin ABS content is added to the material, the failure strain of the material increased to 1.91% accounting to an increase 68% when compared to 60V-40R combination

Young’s Modulus

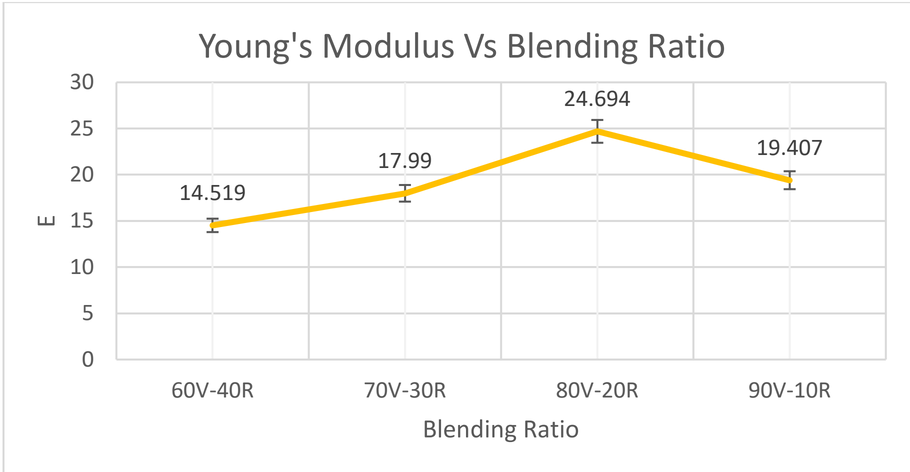


Figure 51 Influence of Blending Ratio on Young's Modulus

From the above graph, it can be deduced that the blending ratio did not have any significant effect on the Young’s modulus of the material. However, a peak in the curve can be observed at the blending combination of 80V-20R.

5.3 Recovery of properties

A. Ultimate Tensile Strength

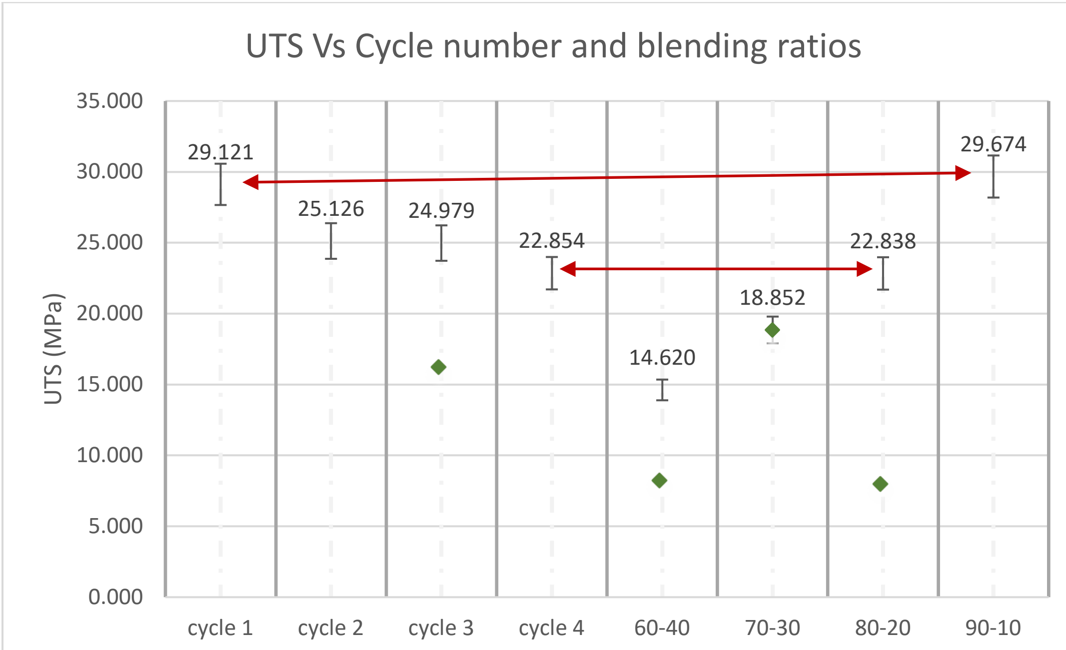


Figure 52 UTS Vs Cycle Number and Blending Ratio

The figure shows the variation in the ultimate tensile strength of the material when subjected to multiple recycling and blending with virgin material. Because of the printing failure of the material, the ultimate tensile strength for cycles 5, 50V-50R AND 60V-40R were considered to be 0 MPa. From the graph, it can be observed that the ultimate tensile strength of cycles 4 and 80V-20R are almost equal. This point (80V-20R) indicates the onset of improvement in the tensile properties of the recyclate material. Similarly, the ultimate tensile strength of cycles 1 and 90V-10R are almost equal. This indicates the recovery of the lost tensile properties in the recycled material.

B. Ultimate Strain

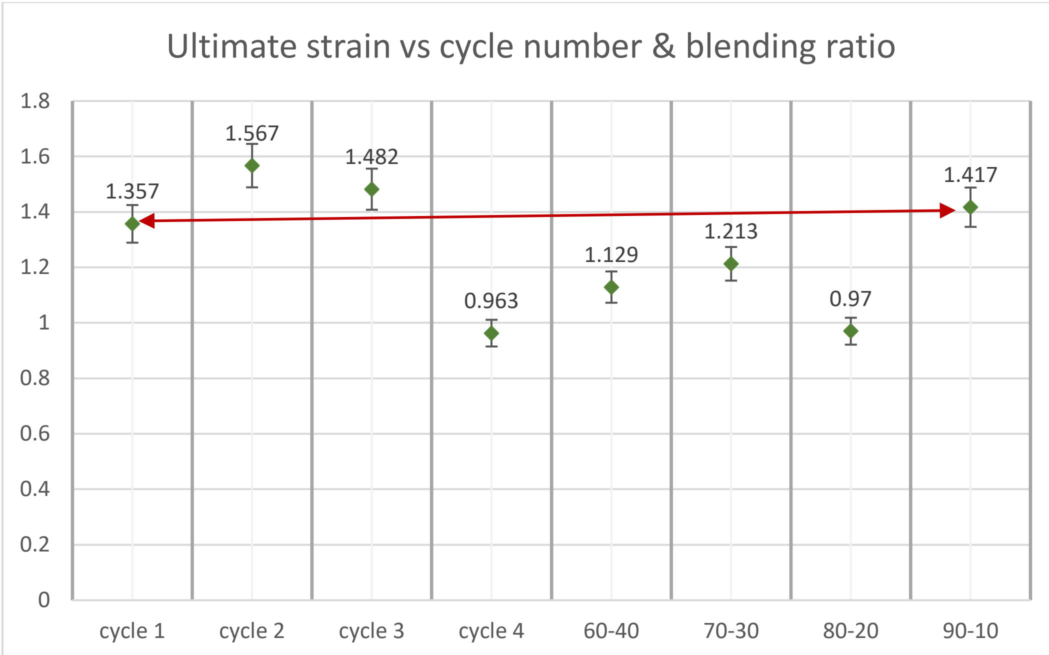


Figure 53 Ultimate Strain Vs Cycle Number and Blending Ratio

This figure represents the variation of the ultimate strain of the material when subjected to multiple recycling and blending with the virgin material. From the figure it can be observed that the ultimate strain of the virgin material and that of cycle 90V-10R are almost equal. Even though, the trend on two sides of the curve is not symmetric, the linear trend line indicates the recovery of the material properties in that 90V-10R cycle that are lost due to repeated recycling.

C. Elongation at Break

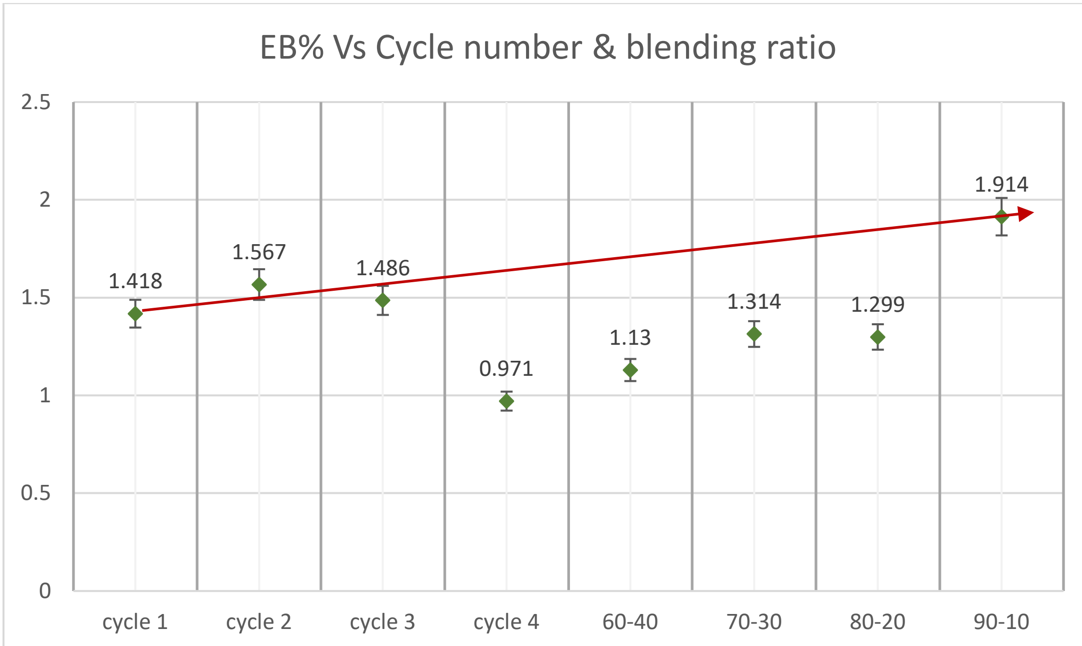


Figure 54 Elongation at Break Vs Cycle Number and Blending Ratio

This figure represents the variation of the failure strain of the material when subjected to multiple recycling and blending with the virgin material. From the trendline in the graph indicated that it is evident that the elongation at break of the material has improved with the introduction of the virgin ABS to the recyclate. The failure strain at the cycle 90V-10R is higher by 30% when compared to that of virgin ABS. This indicates that the blended material has better ductile properties than that of the virgin ABS.

D. Young's Modulus

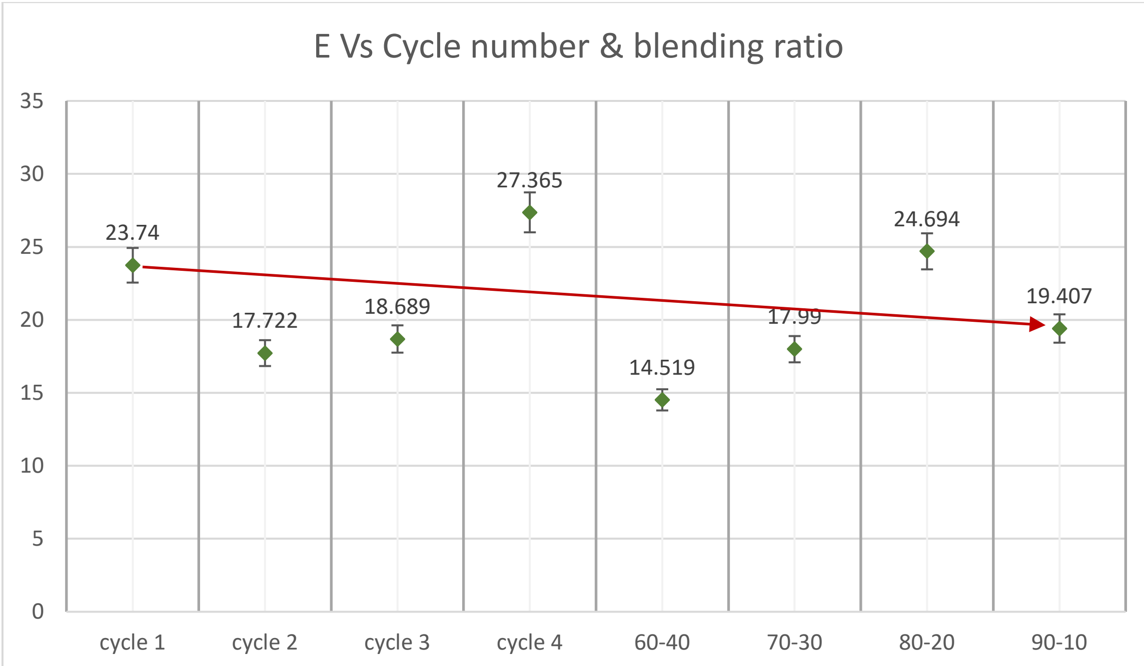


Figure 55 Young's Modulus Vs Cycle Number and Blending Ratio

This figure represents the variation of the failure strain of the material when subjected to multiple recycling and blending with the virgin material. The trendline in the graph indicates that the Young's modulus of the material has decreased with the introduction of the virgin ABS to the recyclate. The Young's modulus of the material at the cycle 90V-10R is lower than that of virgin ABS by 28%. This indicates that the blended material has better ductile properties than that of the virgin ABS.

5.4 Recycling of the Virgin-Recycled ABS Blends

In this section of experiments, the virgin-recycled blends from the previous section, were recycled further, multiple number of times. The purpose of this experimentation is to check if they followed any particular trend in the aging process. To investigate on this, the blends from the previous section were taken, recycled and 3D printed multiple number of times.

For convenience, the following notations were used in this section to represent the recycling cycles-

R – one processing of the blends

RR – Two processing cycles of the blends

RRR – Three processing cycles of the blends

RRRR – Four processing cycles of the blends

As a part of this process, when 70V-30R blend was recycled and used as feedstock for 3D printing, the filament got grounded down in the printer extrusion head, resulting in a printing failure. Thus, only 80V-20R and 90V-10R blends were used further for experimentation.

All filaments in this section exhibited brittle nature, which made them difficult for spooling and subsequent printing.

5.4.1 (80V-20R) RR

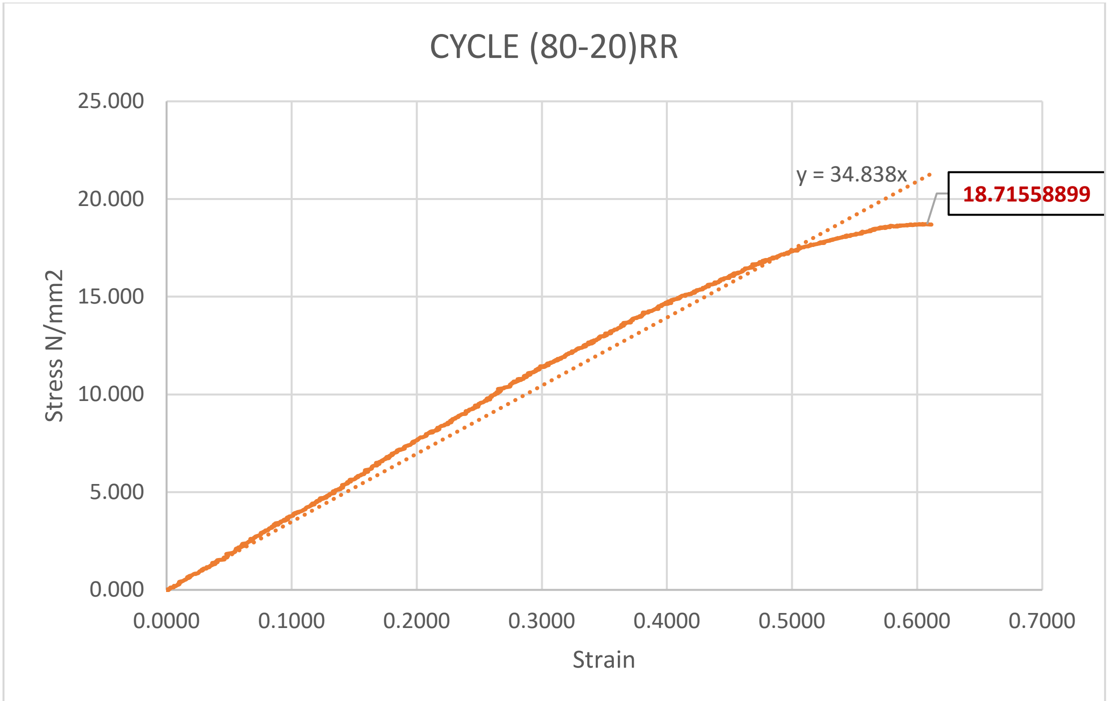


Figure 56 Stress Strain curve of cycle RR(80V-20R)

The dog bone from specimens from cycle (80V-20R)R from the previous experiments were shredded and processed to make (80V-20R)RR specimens for tensile testing. From the above graph, it is evident the ultimate tensile strength (UTS) of the material is 18.718 MPa at a strain of 0.604%. These results show a decrease of 18.04% and 35% in the UTS when compared to the previous cycle and the virgin ABS respectively. In this cycle, the total number of thermal cycles that the virgin part and the recyclate part had undergone was 4 and 13 respectively.

5.4.2 (90V-10R) RR

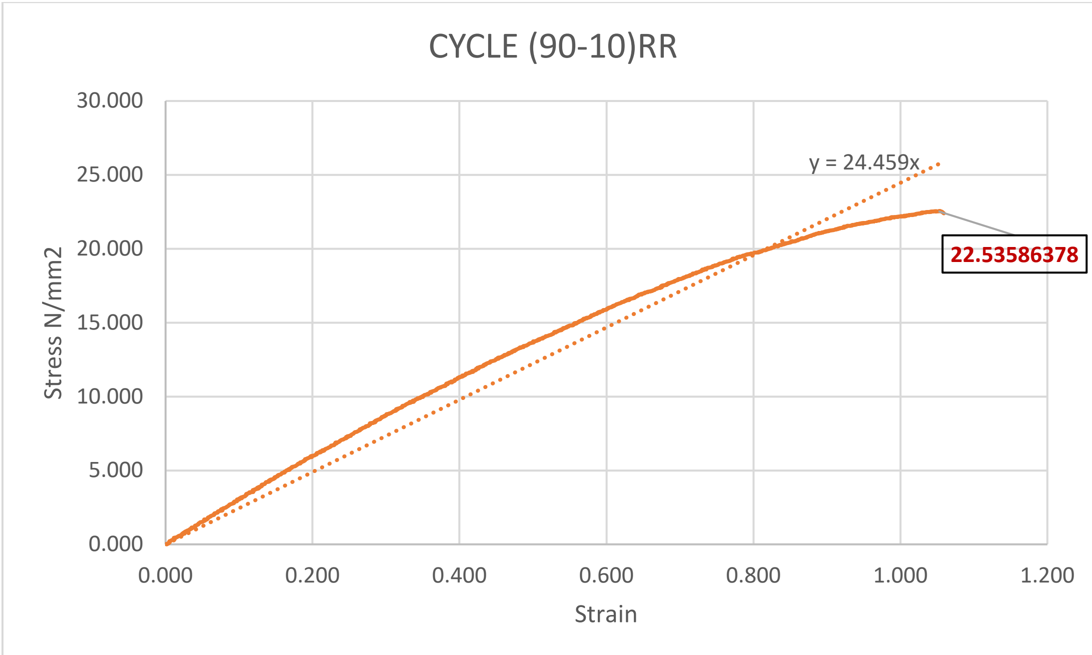


Figure 57 Stress Strain curve of cycle RR(90V-10R)

Similar to process in the section 5.4.2, the specimens from the cycle (90V-10R)R is shredded and processed to make tensile test specimens for the cycle (90V-10R)RR. From the results it can be observed that the ultimate tensile strength of the material is 22.55 MPa at a strain of 1.053%. This indicates that UTS has dropped by 24.06% and 23% when compared to that of (90V-10R)R and virgin ABS material. The total number of thermal cycles that the virgin part and the recyclate part had undergone was 4 and 13 respectively.

5.4.3 (80V-20R) RRR

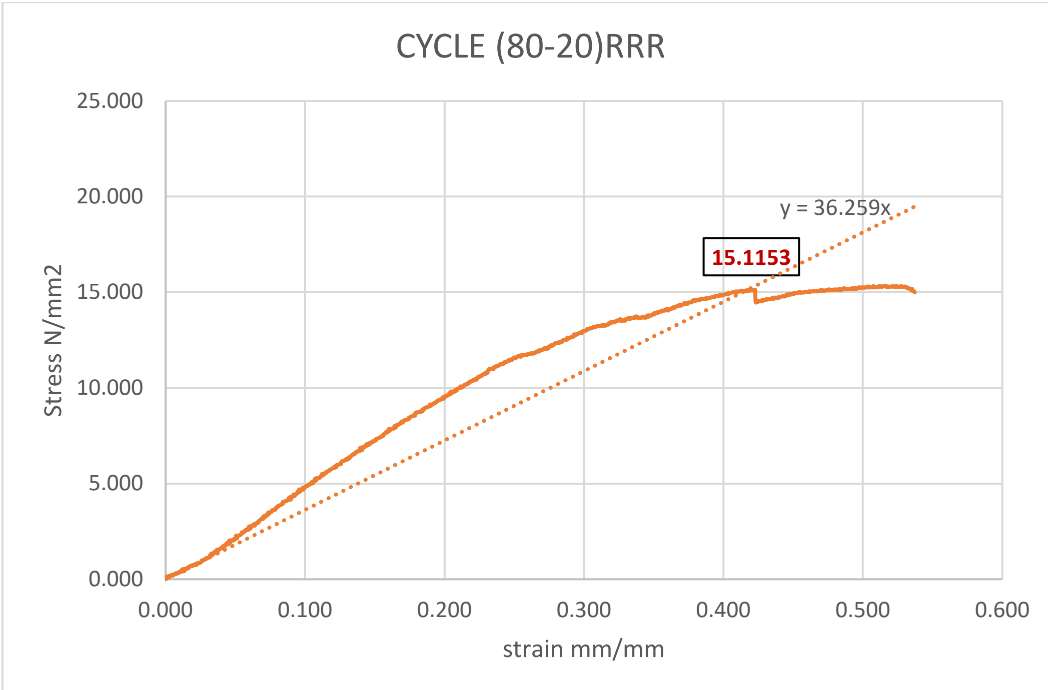


Figure 58 Stress Strain curve of cycle RRR(80V-20R)

In this cycle, the specimens from cycle (80V-20R)RR were reprocessed to make the dog bone specimens for tensile testing. During the testing, the specimens from this cycle broke layer by layer. The kink in the stress strain curve explains this phenomenon. Poor layer to layer adhesion could be the reason for this behavior. For further processing of the data, the failure of the first layer was considered as the point of failure for the specimen. Hence, the ultimate tensile strength (UTS) of this material is 15.11 MPa at a strain of 0.5162%. This is 18.10% and 47.35% less than that of cycle (80V-20R)RR and virgin ABS. The total number of thermal cycles that the virgin material and the recycled material had undergone was 6 and 15 respectively.

5.4.4 (90V-10R) RRR

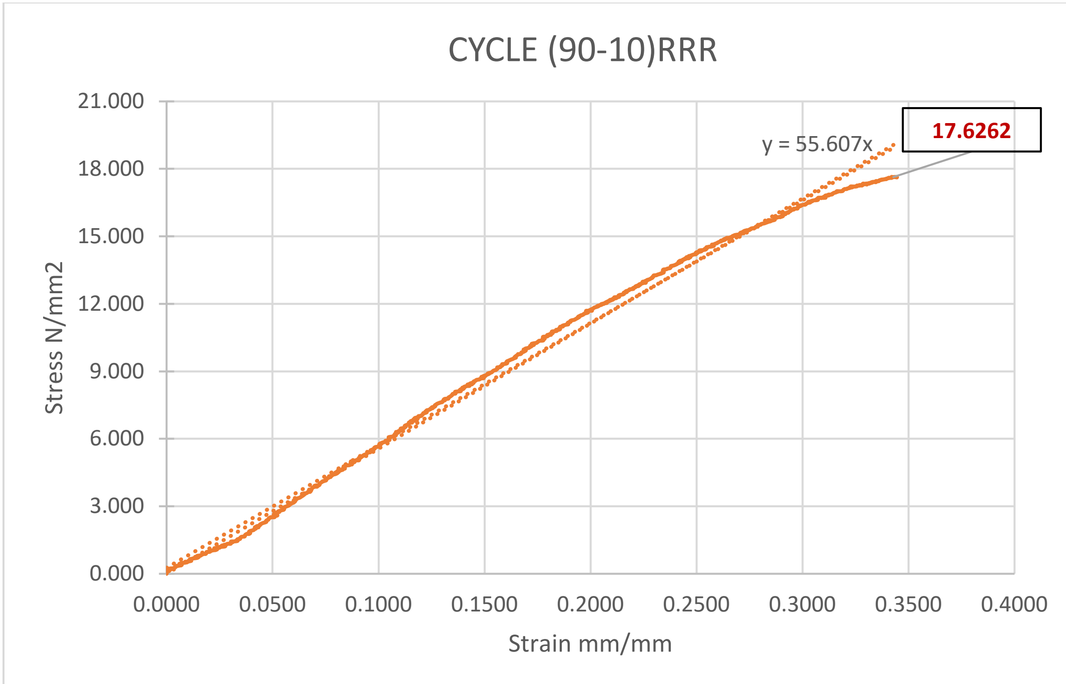


Figure 59 Stress Strain curve of cycle RRR(90V-10R)

In this cycle, the specimens from cycle (90V-10R)RR were reprocessed to make the dog bone specimens for tensile testing. From the obtained data, the ultimate tensile strength (UTS) of this material is 17.64 MPa at a strain of 0.342%. This is 21.76% and 39.407% less than that of cycle (90V-10R)RR and virgin ABS material. The total number of thermal cycles that the virgin material and the recycled material had undergone was 6 and 15 respectively.

5.4.5 Influence of the cycle number of the on the properties

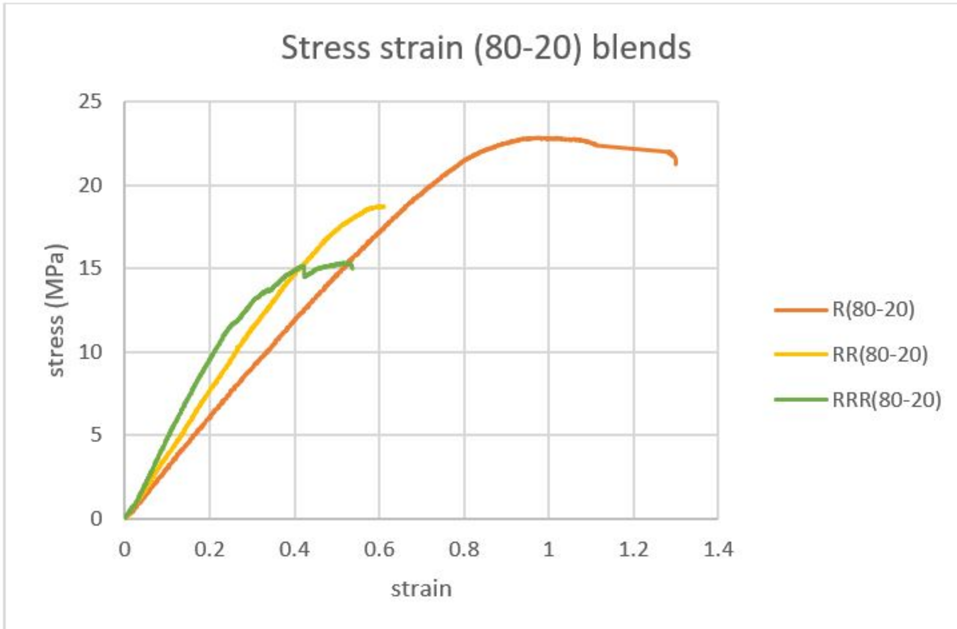


Figure 60 Stress Strain Curves - (80V-20R) Blends

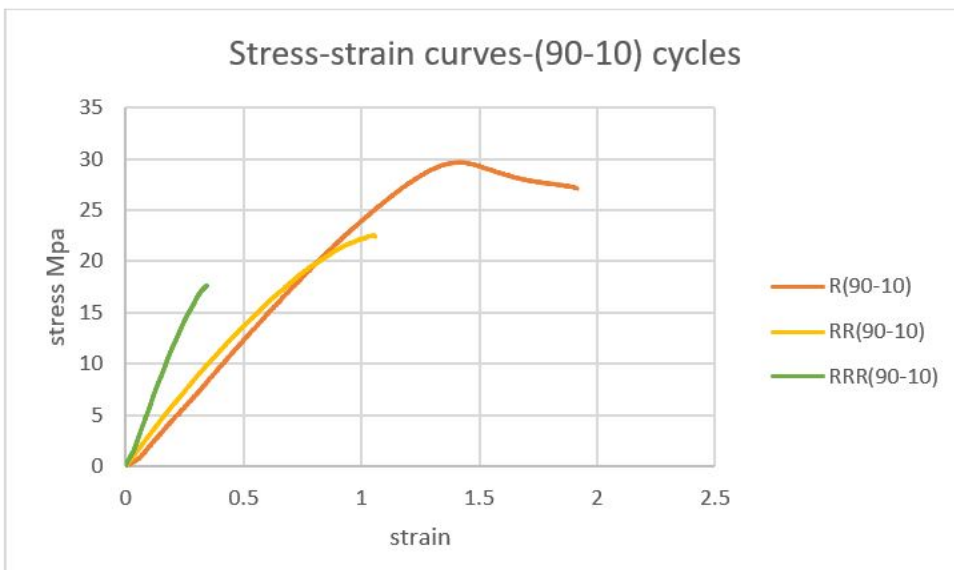


Figure 61 Stress Strain Curves - (90V-10R) Blends

For convenience, all the strain stress curves from this section were plotted on a single graph.

Blending ratio-cycle number	Ultimate Tensile Strength (σ_{ut}) MPa	Ultimate Strain (ε_u %)	Elongation at Break (EB%)	Young's Modulus (E) GPa	Thermal Cycles (V|R)	
80-20R	22.83782	0.97046	1.299207	21.255	2	11
80-20RR	18.7187	0.6043	0.6108	32.775	4	13
80-20RRR	15.3348 (kink)	0.5162	0.5372	29.981	6	15
90-10R	29.6739	1.4170	1.9145	16.101	2	11
90-10RR	22.55399	1.053199	1.059149	21.933	4	13
90-10RRR	17.6453	0.3420	0.3445	54.452	6	15

Table 10 Mechanical properties of multiple recycling cycles of different blends of ABS

From the above table, it can be observed that the ultimate tensile strength (UTS), ultimate strains and elongation at break (EB%) of the blended materials decreased with an increase in the recycling cycles. The Young's modulus in the series of (90V-10R) cycles showed an increasing pattern with an increase in the cycle number. This trend of decreasing strains and the increasing Young's modulus with respect to cycle number, indicates the increasing brittle nature in the material when subjected to multiple recycling.

When the material from specimens (90R-10V)RRR and (80R-20V)RRR was subjected to fourth recycling cycle (RRRR), black specs were significant on the filament indicating a degradation in the material. When the filament from (80V-

20R)RRRR batch was used for 3D printing it got grounded up in the extruder head. Though, the filament from (90V-20R)RRRR batch passed through the printer head, the print failed at its second layer, indicating poor adhesion between the layers.

A. Ultimate Tensile Strength

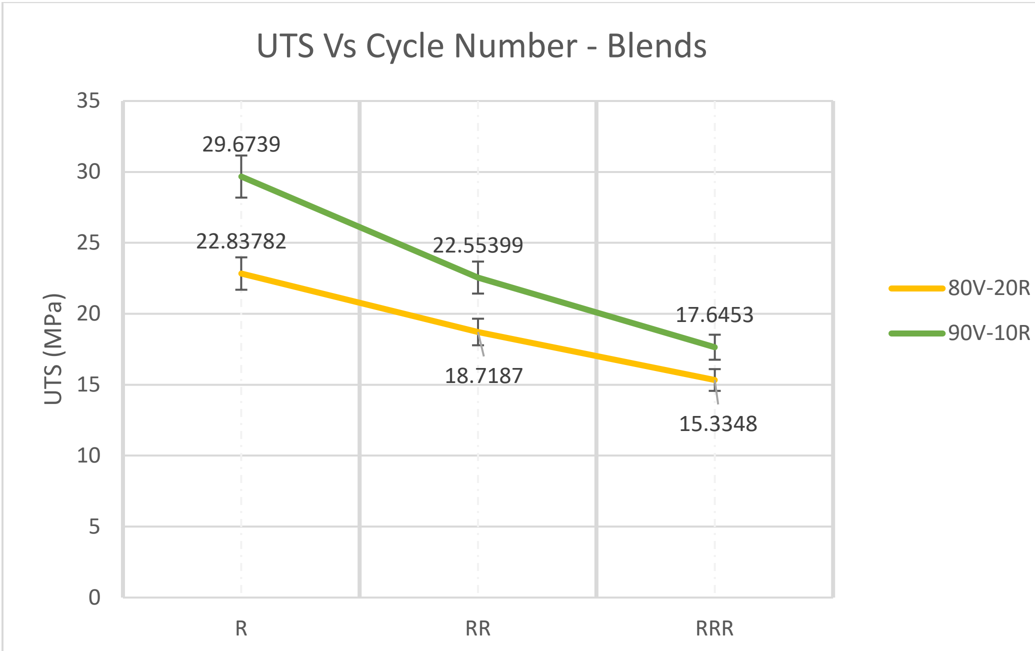


Figure 62 Influence of Cycle Number on the UTS - Blends

This graph indicates the variation of UTS with respect to the recycling cycle number. From the graph it can be deduced that the ultimate tensile strength of both the blends followed a similar trend of decreasing with respect to the cycle number.

B. Ultimate Strain

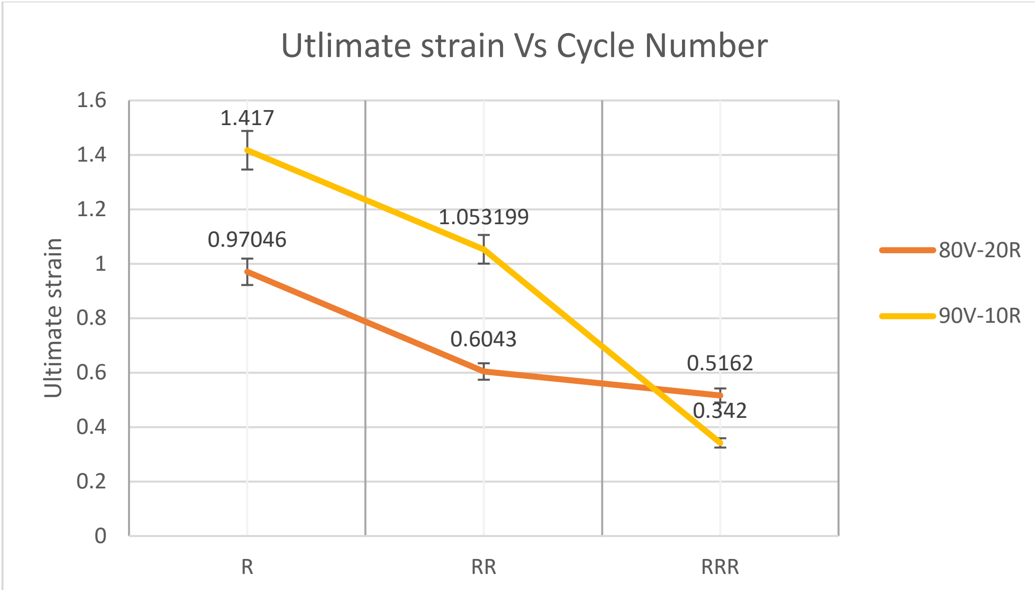


Figure 63 Influence of Cycle Number on the Ultimate Strain - Blends

This graph indicates the variation of ultimate strain with respect to the recycling cycle number. From the graph it can be observed that the ultimate strain of both the blends decreased with the increase in the cycle number.

C. Elongation at Break

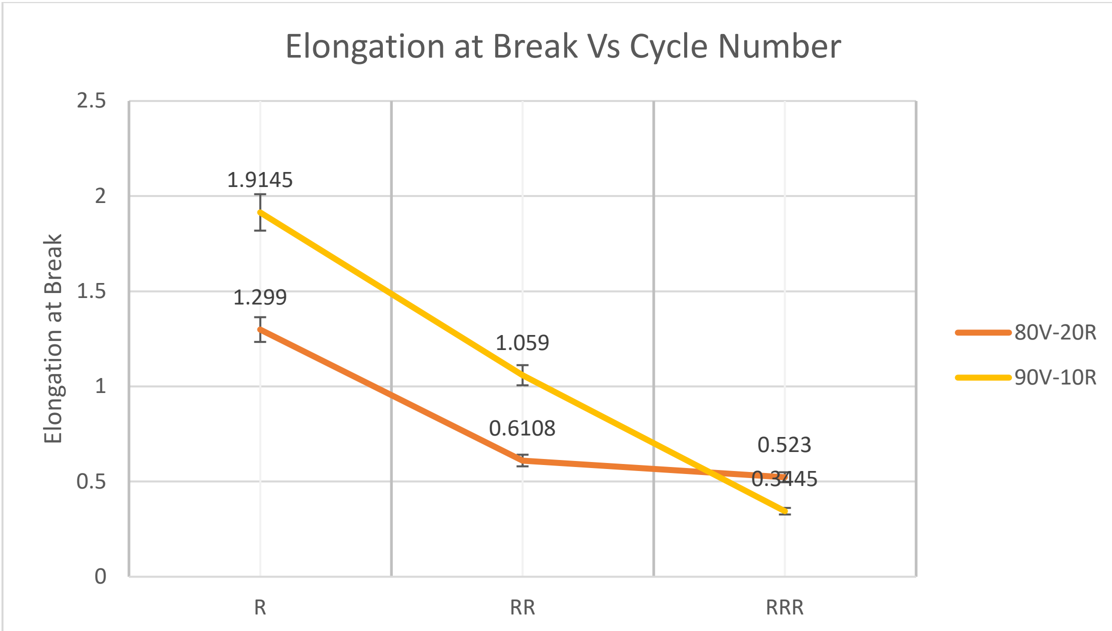


Figure 64 Influence of Cycle Number on the Elongation at Break - Blends

This graph indicates the variation of elongation at break with respect to the recycling cycle number. From the graph it can be observed that the elongation at break (EB%) of the (90V-10R) blend decreased with the increase in the cycle number. However, in the case of (80V-20R) blend, though the EB% was decreased by 51% from R to RR, the cycle number did not any significant effect on it further.

D. Young’s Modulus

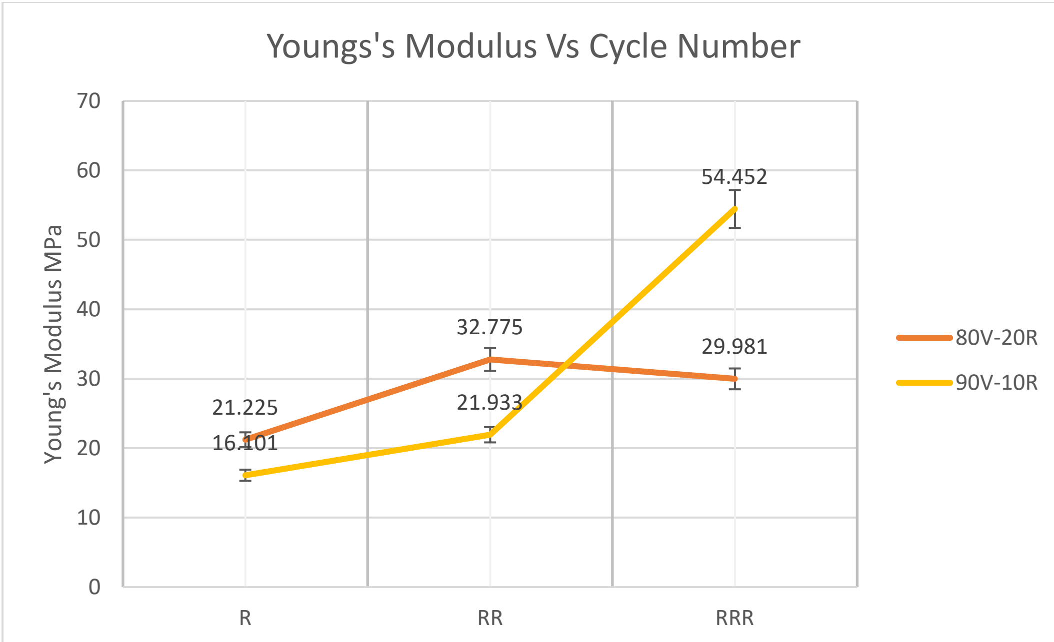


Figure 65 Influence of Cycle Number on the Young's Modulus - Blends

This graph indicates the variation of Young’s Modulus with respect to the recycling cycle number. From the graph it can be observed that the Young’s modulus of the (90V-10R) blend increased tremendously with the increase in the cycle number. However, though the Young’s modulus of the (80V-20R) blend initially increased from cycle R to RR, it decreased by 6.8% on further recycling.

Chapter 6

Conclusions and Future Work

6.1 Research Conclusions

The increasing 3D printing user domain and the growing demand for plastics in the recent past, posed a serious question of plastic recycling and its disposal. This raised an increased scope on studying the properties of the plastic when subjected to recycling in the context of additive manufacturing. Through our study – "Analysis of mechanical properties of 3D printed recycled ABS", we were able to investigate the mechanical behavior of additively manufactured ABS polymer when subjected to ageing and recycling. This study on the behavior of recycled ABS polymer helps in estimating and finding its applications based on the level of ageing.

In this study, 3D printed ABS polymer was subjected to multiple recycling, until the material was no longer printable. It was observed that the material failed after the fifth recycling cycle. This answers the question of mechanical recyclability of 3D printed ABS polymer. This printing failure is associated with an increase in the material's brittleness and a decrease in the layer-to-layer adhesion, indicating a loss in the properties and the degradation of the material.

From the tensile test results, a depletion in the tensile properties of the material was observed with the increasing cycle number. In specific from cycle – 1 to cycle – 4, the ultimate tensile strength of the material decreased by 22.11%. Similarly, the ultimate strain of the material decreased by 28% and the Young's modulus of the material increased by 1.4% for the same. These changes in the mechanical properties indicate an increase in the brittle nature in the material. Because of this brittle nature, by the end of fifth cycle, the filament used for 3D printing fragmented in the extruder head resulting in a printing failure. A similar phenomenon was observed by Bai et al., who studied the mechanical behavior of injection molded recycled ABS with respect to the recycling number. Their group observed a decrease of 44% in the impact strength of the material from cycle – 1 to cycle – 4. This decrease in the impact strength indicates an increase in the brittleness in the material. Their study suggests that this behavior of the material is due to cross linking of the rubber phase and scissions in the polymer chains. Since the two experiments had similar effect on the material, it can be concluded that reprocessing of ABS polymer has a deteriorating effect on its mechanical properties.

In the second part of our study, virgin ABS at various percentages was blended with the recycled ABS, to determine if we can recover any of the properties of the recycled ABS. From the test results, it was observed that the ultimate tensile strength, ultimate strain and % elongation at break of the material improved with increase in the percentage of virgin material in the blend. Printing failures were observed with blends that have more 50% of recycled ABS in them. From cycle 60V-40R to cycle 90V-10R, the ultimate tensile strength of the material improved by almost 100% and the ultimate strain by 25%. However, the Young's modulus of the material was not affected by the blending ratio. A similar trend in the tensile strength of the material was observed by Scaffaro et al. Their group studied on the mechanical behavior of the virgin and post-consumer blends of injection molded ABS. They observed an increase in the tensile strength with increasing content of the virgin ABS. From these two observations, it can be deduced that the addition of virgin ABS to the recycled material has a positive effect and it improves with increasing content of virgin ABS.

In addition to that, 90V-10R blend with 90% of virgin and 10% recycled ABS displayed similar properties to that of virgin ABS. The ultimate tensile strength and the ultimate strain of both the materials were almost equal. However, the 90V-10R blend showed a slightly higher % elongation at break and lower Young's modulus, indicating a better plastic behavior than the virgin ABS. On the whole, these values indicate that introducing virgin material allows for the recovery of properties that are lost due to mechanical reprocessing in the ABS polymer.

In the fourth part of our study, the virgin – recycled ABS blends were further reprocessed to check if they exhibited trends in the ageing process. From the results, it was observed that the tensile properties of the material deteriorated with the increase in the cycle number, similar the trend observed in the first set of the experiments. However, the rate of deterioration was observed to be drastic in this case. This might be because of the presence of already-recycled ABS in the filament. So, further reprocessing of this material, resulted in a rapid depletion in the properties. The results from this experiment demonstrated the effect of ageing on the virgin material that is blended with the recycled ABS.

The problem statement of – "Determining the effect of recycling on the mechanical properties of ABS polymer for additive manufacturing", was investigated and answered through this study. The best approach to study and recycle the polymer to reuse it for additive manufacturing, is to process the used ABS into a filament and 3D printing it into tensile test specimens for analysis. According to the analysis, ABS polymer is good to use, as feedstock for 3D printing for about four recycling cycles. After this repeated recycling, blending it with 90% of virgin ABS is a best way to recover its properties that are lost due to reprocessing.

6.2 Future Scope

This research has answered many questions in the context of recycling of ABS. However, it has created additional scope for further investigations. The opportunities for future work include:

1. Developing a system that can recycle and 3D print the polymer in a single stretch, without having the need to process the polymer into a filament. This system would help in eliminating a thermal cycle, that the material must undergo in the extrusion process. This elimination of a thermal cycle would subsidize the amount of thermal degradation that the material undergoes and might help in achieving better set of properties.
2. Investigating the effect of recycling on the chemical composition of the ABS polymer. This kind of investigation would tell us which component of ABS is most effected by the mechanical recycling. Thus, doping that particular component into the recycled ABS would yield better property recovery. This also can provide better understanding of the applications of recycled ABS.
3. Investigating an approach for the addition of other possible dopants that could improvise the properties of the recycled ABS. From the current research, we have the answers on how the properties of recycled ABS vary, addition of dopants that could add desirable effects to the recycled ABS would yield beneficial results.
4. Studying the effect of extruder and the printer operating temperatures on the mechanical properties of recycled ABS. From the current it is evident that the

MFI of the material was influenced by the recycling cycle number. Basing on this information, studying on how the operating temperatures would affect the mechanical properties at each cycle of would yield interesting results. This can further provide a scope to study on the thermal degradation of the material.

5. All the samples in the current study were printed at 100% infill density. However, the influence of the infill density on the mechanical properties of the recycled ABS still has a scope to be investigated. So, investigating the mechanical properties of the recycled ABS by varying the infill density and every reprocessing cycle, would furnish us with further information on the mechanical behavior of recycled ABS.
6. Investigating the mechanical properties of the specimen that is 3D printed by sandwiching the recycled ABS in between the layers of virgin ABS or vice-versa and varying the number or percentage of virgin and recycled ABS layers. As the recycled ABS exhibited and virgin ABS exhibited different mechanical behavior, this experimentation might yield some interesting findings.

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